An Analytical Model of Quad Cable to 1 GHz: Part 2

Tom Perkins: Commercial and Defense Microwaves: Do They Enhance One Another?

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<table>
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<tr>
<th>Connector Series</th>
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<tr>
<td>1.85mm</td>
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<tr>
<td>2.92mm</td>
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22: Feature Article

An Analytical Model of Quad Cable to 1 GHz: Part 2
By Kenneth S. Schneider

Transmission lines -- basically telephone network local loops -- used by these technologies for the transmission media, present many different and complex characteristics at these microwave frequencies -- characteristics which were either unknown or ignored until relatively experimental measurements uncovered them. These characteristics may well affect the performance of the new broadband technologies. The model presented captures these characteristics analytically and can be used as a guide in developing simulation equipment for the testing of these technologies. The model presented includes the direct path attenuation, phase (Group Delay), input impedance and Characteristic Impedance of the direct path-single line loop. The model includes the characterization of Far End Crosstalk, FEXT and especially the “normalized” FEXT (ELFEXT) both within a single Quad (Intra-Quad) -- which is often alternatively referred to as “In-Quad” -- and between Quads (Inter-Quad). After presentation, this model is compared to experimental measurements made with an actual Quad Cable in current use. The model presented is derived as a further development of the approach to this problem presented by Youla [1]. This is based essentially upon Maxwell's equations and the electro-magnetic theory associated with transmission lines -- but applied to multiple transmission lines -- essentially a matrix-vector extension of the “traditional” transmission line equations.
The future holds unforeseen challenges. Lowest latency communications can help overcome the toughest challenges. Analog Devices’ system-level expertise in RF, microwave and millimeter wave technology helps unlock the entire wireless spectrum, and the opportunities that come with it. Learn more at analog.com/RF.
High Frequency Electronics

At the recent IEEE International Microwave Symposium in Boston, Strategy Analytics held a Lunch & Learn titled: Can Commercial Networks Learn from Defense Technologies (and Vice Versa)? Having worked in defense related microwaves for most of my career, while having an underlying interest in communications as a radio amateur for even longer, and most recently having acquired knowledge of cellular networks, I can appreciate a confluence of techniques and hardware that now enables people worldwide to benefit from our labors. Eric Higham, Director or SA’s Advanced Semiconductor Applications, discussed subjects such as defense use of the internet, shared spectrum, Active Electronically Scanned Arrays (AESAs), and Massive MIMO.

An AESA is a type of phased array antenna which is computer controlled where the beam can be electronically steered to a point in different directions without physically moving the antenna. This technique has found its way into the commercial world for steering pinpoint beams.

Nomadic 5G was also mentioned. Having curiosity about such a concept, I found that this could refer to private networks, e.g., inter-connected off-road vehicles like agricultural harvesters, tandem rollers, or airport vehicles that are independent from the network infrastructure. These are usually private networks. Scenarios include millimeter-wave technology for short range high bandwidth communication and ranging.

History Lesson

I well remember the Microwave and Millimeter Wave Integrated Circuit (MIMIC) Program sponsored by DARPA that ran from about 1987 to 1995, directed primarily by Eliot Cohen. This program, which funded numerous defense contractor semiconductor foundry efforts, led to production of low cost and reliable gallium arsenide (GaAs) FET circuitry. This in turn greatly enabled proliferation of millions of cell phones and more recently, Internet of Things, vehicular radar, and much more.

This two-way “handshake” of technology reminds me of a classic commercial to defense hand-off that occurred at the outset of World War II. It is an example of shared technology in a less sophisticated, but nonetheless critical time requiring rapidly deployable military assets. In those days there suddenly was an enormous need for shortwave receivers and transmitters and electronic parts.
Except for some VHF/UHF communications activity called War Emergency Radio Service (WERS) established in June 1942, the amateur radio system was shut down. Actually, WERS was not amateur radio, but it was mostly run by amateurs in the old 2 ½ and 1 ¼ meter bands. Apparently, communities were issued the station licenses and hams provided the operating skills. At peak there were 5,000 transmitters operated under 250 special licenses. Unlike during WWI, however, during WWII only transmitting in the short-wave bands was banned. Receiving signals was not only permitted, but encouraged. Antenna installations, for the most part, remained elevated. Due to the sudden military shortages, many amateurs donated their equipment to the war effort, particularly like short-wave high-quality commercially manufactured receivers like the National Radio Company’s HRO-M. A former National Radio employee told me in 1986 that HRO stood for “helluva rush order.” Also, much like scrap metal, things like D’Arsonval movement panel meters and transmitting vacuum tubes, such as 807s, were collected for military use.

The Federal Communications Commission (FCC) handled the amateur radio shutdown in a clever manner. Back then there was a clear distinction made between operator and station licenses. The FCC suspended the amateur station licenses. They continued to hold license exam sessions and issue operator licenses only.

In my research I found that apparently the German military operating VHF radios in France did not realize they could be heard in Great Britain. This actually illustrates the value of knowledge likely gained by hobbyists, as VHF communications was in its infancy.

Another defense to commercial example: the once highly classified magnetron of radar fame is now in almost every kitchen.

**Ponder This**

So, I close with an observation and a question. There is no doubt that defense research has hastened the current state of commercial microwave proliferation. Our commercial cellular communications infrastructure now greatly exceeds that of the military communications networks, sort of the way that the Eisenhower highway system built in the 1950s could provide emergency military aircraft takeoff/landing strips if the automobiles and trucks were removed. If in the event of a war situation, which we hope never happens, would we be willing to sacrifice our cellular assets to the military? Our frequency bands used for entertainment such as satellite TV to military aircraft operations? Our amateur radio repeaters? And even our personal wi-fi compatible equipment which may not even yet exist?
Meetings and Events

See: https://conferences.ieee.org/

2019 Second International Workshop on Mobile Terahertz Systems (IWMTS)
1 - 3 July 2019, Bad Neuenahr, Germany
Sponsors: IEEE Microwave Theory and Techniques Society; University of Duisburg-Essen
Field of Interest: Components, Circuits, Devices and Systems; Computing and Processing; Fields, Waves and Electromagnetics; Photonics and Electrooptics; Signal Processing and Analysis

2019 IEEE MTT-S International Microwave Workshop Series on Advanced Materials and Processes for RF and THz Applications (IMWS-AMP)
16 - 18 July 2019, Bochum, Germany
Sponsors: European Microwave Association - EuMA; IEEE Microwave Theory and Techniques Society
Field of Interest: Bioengineering; Communication, Networking and Broadcast Technologies; Components, Circuits, Devices and Systems; Engineered Materials, Dielectrics and Plasmas; Fields, Waves and Electromagnetics; Photonics and Electrooptics

2019 IEEE MTT-S International Microwave Conference on Hardware and Systems for 5G and Beyond (IMC-5G)
15 - 16 August 2019, Atlanta, Georgia, USA
Sponsors: Georgia Institute of Technology; IEEE Microwave Theory and Techniques Society
Field of Interest: Communication, Networking and Broadcast Technologies; Components, Circuits, Devices and Systems; Fields, Waves and Electromagnetics; Photonics and Electrooptics

2019 12th UK-Europe-China Workshop on Millimeter Waves and Terahertz Technologies (UCMMT)
20 - 22 August 2019, London, United Kingdom
Sponsors: IEEE Microwave Theory and Techniques Society; IEEE Photonics Society; Queen Mary University of London
Field of Interest: Communication, Networking and

2019 44th International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz)
1 - 6 September 2019, Paris, France
Sponsors: IEEE Microwave Theory and Techniques Society; International Society of Infrared, Millimeter, and Terahertz Waves
Field of Interest: Aerospace; Bioengineering; Communication, Networking and Broadcast Technologies; Components, Circuits, Devices and Systems; Engineered Materials, Dielectrics and Plasmas; Fields, Waves and Electromagnetics; Photonics and Electrooptics

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https://wie.ieee.org/leadership-summits2019

Broadcast Technologies; Components, Circuits, Devices and Systems; Engineered Materials, Dielectrics and Plasmas; Fields, Waves and Electromagnetics; Photonics and Electrooptics

2019 IEEE International Symposium on Radio-Frequency Integration Technology (RFIT)
28 - 30 August 2019, Nanjing, China
Sponsors: IEEE Microwave Theory and Techniques Society; Southeast University, China
Field of Interest: Communication, Networking and Broadcast Technologies; Components, Circuits, Devices and Systems; Fields, Waves and Electromagnetics; General Topics for Engineers; Power, Energy and Industry Applications

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Wi-Fi Celebrates 20 Years; More Than 20 Billion Device Shipments Anticipated

More than 20 billion Wi-Fi devices are forecasted to ship between 2019 and 2024, according to a new market data report from global tech market advisory firm, ABI Research. Continued growth in traditional markets of strength, alongside traction in mesh networking systems, smart home, automotive, and IoT applications will drive the Wi-Fi market forward to nearly 4 billion annual device shipments by 2024.

“2019 marks the 20th anniversary of Wi-Fi, though the technology shows no signs of slowing down,” says Andrew Zignani, Principal Analyst, ABI Research. “Wi-Fi 6 is quickly gaining momentum in networking devices, while client devices are already arriving into the market and are anticipated to ramp up considerably over the next 12-18 months. The need for faster, more reliable, more efficient, and more widespread Wi-Fi coverage is becoming increasingly vital in a world filled with more Wi-Fi devices at both ends of the performance spectrum, from high resolution streaming and low latency gaming to battery constrained IoT devices,” says Zignani.

Wi-Fi’s expansion into the 6GHz and sub-1GHz bands through WiGig and HaLow have been considerably slower, though ABI Research anticipates these technologies will carve out their own success in the coming years. “WiGig still has considerable potential for point-to-point applications such as wireless video streaming, virtual reality, and docking, and has recently seen considerable traction in fixed wireless access applications. HaLow chipsets and IP are finally coming to the market thanks to efforts from start-ups as Newracom, Morse Micro, and Palma Ceia SemiDesign among others, and the inherent flexibility of the technology could make it very attractive in LPWA type applications,” says Zignani.

However, most exciting of all is the anticipated availability of 6GHz spectrum over the next few years. “Though there is much work to be done here from a regulatory perspective, the addition of a possible 1.2GHz of additional spectrum for Wi-Fi that will be unencumbered by legacy Wi-Fi technologies could lead to an unprecedented performance and capacity boost for Wi-Fi in the future,” says Zignani. “The Wi-Fi 6 standard is adding support for 6GHz capabilities, and work is already underway for the next generation that will take full advantage of the new spectrum. These enhancements combined will ensure that Wi-Fi will continue to drive value well into its 30th anniversary and beyond,” Zignani concludes.

These findings are from ABI Research’s Wireless Connectivity Technology Segmentation & Addressable Markets market data. This report is part of the company’s Wi-Fi, Bluetooth and Wireless Connectivity research service, which includes research, data, and analyst Insights. Market Data spreadsheets are composed of deep data, market share analysis, and highly segmented, service-specific forecasts to provide detailed insight where opportunities lie.

—ABI Research
abiesearch.com

Rural Communities Drive $20.2 Billion in Rural Cell-site Expenditures in 2019

There is a growing divide in terms of the quality of mobile broadband coverage between rural and urban communities. Mobile operators are responding to local community and state regulatory pressure to ensure mobile cellular coverage is not just “voice-capable” but also “mobile broadband-capable.” In 2019, an estimated US$20.2 billion will be invested in developed and emerging market rural cell-sites, a 1.2% increase from 2018, reports ABI Research.

Mobile operators and infrastructure vendors are also in the process of rebooting the typical cell-site deployment approach. The macro base-station is now being complemented by low-cost small cells that deliver coverage to a specific rural village or town. Small cell unit shipments will grow at a compound annual growth rate of 10.9% to reach US$2.2 billion by the end of 2024.

“Novel engineering and manufacturing processes have not just made rural cell-site solutions cheaper but also more versatile,” says Ling Kangrui, Research Analyst at ABI Research. “Innovative re-inventions of the traditional cell site include Huawei’s RuralStar Lite and Nokia’s Kuha cell-site. Huawei claims that it has been able to reduce the cost of its RuralStar Lite solution to around US$20,000 and therefore offers a lower return of investment time of between three to five years. The Facebook-backed Telecom Infra Project (TIP) ventures, such as Parallel Wireless vRAN and Fairwaves base station solutions, have radically altered the typical cell-site total cost of ownership model for the operator. Furthermore, tethered and untethered, “balloon-based” solutions such as Altaeros’ SuperTower and Alphabet’s Loon will potentially disrupt the macro cell-site business model,” Kangrui explains.

—ABI Research
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Enabling Revolutionary Nondestructive Inspection Capability

X-rays and gamma rays have a wide range of applications including scanning suspicious maritime shipping containers for illicit materials, industrial inspection of materials and processes, and medical diagnostic and therapeutic procedures. Current technologies, however, are not ideal. X-rays produce a continuum of energies that limit their inspection and diagnostic performance, and gamma rays can only be produced at specific energies unique to a given radioactive isotope.

DARPA announced its Gamma Ray Inspection Technology (GRIT) program. GRIT seeks novel approaches to achieve high-intensity, tunable, and narrow-bandwidth sources of gamma ray radiation in a compact, transportable form factor that would enable a wide range of national security, industrial, and medical applications.

“What we’re trying to do in GRIT is transform the use of x-rays and gamma rays,” said Mark Wrobel, program manager in DARPA’s Defense Sciences Office. “Current sources of gamma rays, like Cobalt-60 or Cesium-137, are not very flexible. They require special licenses to possess and only emit gamma rays at very specific energies. What we desire is a source of very high-energy photons that we can tune to match the application we need. This ranges from more effective detection of illicit cargo, to a more informative medical x-ray.”

GRIT aims to provide a source of tunable, pure x-rays and gamma rays from tens of keV (kilo-electron volts) up through over ten MeV (mega-electron volts). Currently, tunable and narrow bandwidth gamma ray sources only exist at highly specialized user facilities best suited for basic research and are not able to support broad practical applications. Shrinking these photon sources to a transportable system is a major goal and challenge of the GRIT program.

GRIT technology could make possible a range of new inspection and diagnostic protocols. In medical and industrial radiography, for example, GRIT could enable revealing specific elemental and material content, such as calcium in bones or specific metals in cargo. A typical x-ray only shows differences in density in the object being inspected – whether a piece of luggage at an airport, or an individual at a doctor’s office. If successful, a GRIT x-ray source could be tuned to detect and quantify the concentration of specific elements of interest, such as the amount of calcium in a given bone x-ray, enabling radiologists to actually see bone composition.

Tuning energy between 10s of keV to over 100 hundred keV would allow detection of specific elements that might be of interest in characterizing novel materials and processes at micron scales. These techniques would be relevant to defense applications including non-destruction inspection of novel additively manufactured materials and alloys for their elemental composition.

At energy levels in the MeV range, gamma ray photons have high enough energy to actually interact with the nuclei of atoms. Whereas x-rays work by interacting with the shells of atoms, GRIT would be able to stimulate the nucleus of an atom to bring about an effect called nuclear resonance fluorescence, a sort of “fingerprint” that is unique to each isotope of every element in the periodic table.

“With GRIT, you could probe and detect specific isotopes of interest by fine-tuning the photon energy to minimize background noise and take advantage of the nuclear resonance fluorescence phenomenon,” Wrobel said. “Those isotopes could be found in rare-earth elements of interest or special nuclear materials. To be able to definitively say, ‘Yes, there’s highly enriched uranium in this object’ and be able to characterize how much is present would be a significant leap forward over our current capabilities.”

DARPA is seeking expertise in a range of technologies on the GRIT program including advanced accelerator technology, high-energy laser systems, novel control systems, and new x-ray and gamma ray detector technology. GRIT’s focus on new, compact photon sources for inspection complements DARPA’s Intense and Compact Neutron Sources (ICONS) program, which is developing compact neutron sources. The two technologies would work in tandem, yielding a very robust inspection capability.

—DARPA
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<th>Model</th>
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In the News

Raytheon Honors Lansdale Semi

R. Dale Lillard, President, Lansdale Semiconductor, recently announced that the company was honored for the sixth consecutive year by Raytheon Integrated Defense Systems for Supplier Excellence. This year, Lansdale achieved Raytheon’s highest 5 Star Award.

Raytheon’s Integrated Defense Systems business instituted the annual Supplier Excellence Awards program to recognize suppliers who have provided outstanding service and partnership in exceeding customer requirements. Award candidates are judged on certain criteria, including overall quality, on-time delivery and demonstrated commitment to continuous improvement. A 5 Star recognition is the highest level of recognition a Raytheon Integrated Defense Systems business supplier can achieve for excellence in quality and performance, and Lansdale Semiconductor, Inc. was one of only 16 companies selected.

* * *

Lockheed Martin Honors Custom MMIC

Lockheed Martin recognized 27 small business suppliers that made exemplary contributions to its Missiles and Fire Control business area’s products and services in 2018. Custom MMIC received an award for their exemplary work in helping Lockheed Martin deliver crucial missions to their customers.

Paul Blount, President and CEO of Custom MMIC, and Charlie Trantanella, Chief Scientist, attended the award ceremony and accepted the award on behalf of the Custom MMIC team. “We are excited and honored to have been selected for this prestigious award from Lockheed Martin,” said Paul Blount. “This acknowledgement validates Custom MMIC’s tireless commitment to providing the best products and services possible to our valued customers and partners now and for the future.”

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</table>

Note 1. Insertion Loss and VSWR tested at -10 dBm.
Note 2. Power rating derated to 20% @ +25 Deg. C.
Note 3. Leakage slightly higher at frequencies below 100 MHz.

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Richardson RFPD announced availability and full design support for a new silicon carbide module from Wolfspeed. Wolfspeed developed the XM3 power module platform to maximize the benefits of SiC, while keeping the module and system design robust, simple and cost-effective. With half the weight and volume of a standard 62 mm module, the CAB450M12XM3 maximizes power density while minimizing loop inductance and enabling simple power bussing. It is the first part to be launched in the XM3 module platform, with additional offerings to be released in the future.

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**Anritsu Company**
[anritsu.com](http://anritsu.com)

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### 26.5 GHz RF Downconverter
The SC5318A is a C to K broadband single-stage downconverter, converting frequencies from 6 GHz to 26.5 GHz down to 50 MHz to 3 GHz. The LO frequency range is from 6 to 26.5 GHz with an input LO range from 6 to 14 GHz. An internal frequency doubler multiplies the input LO range up to 26.5 GHz. This module also features an internal 26.5 GHz synthesized LO, RF preamplifier, and variable gain control, making it a compact, standalone downconverter module. The SC5318A can be combined with SignalCore’s SC5308A to form a broadband 100 kHz to 26.5 GHz downconverter. These high-performance converter modules are compact and rugged, built for easy integration into large systems.

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<td>80</td>
<td>250 ns</td>
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<td>-5 V @ 200 mA</td>
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<td>9.5</td>
<td>60</td>
<td>100 ns</td>
<td>+5 V @ 1450 mA</td>
<td>-5 V @ 20 mA</td>
<td>SP32T</td>
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</table>

### Dimensions

- **Configuration:** (Inches)
  - **Size:** 1.2” x 1.25” x 0.4”
  - **Connectors:** 2.92mm (F)

- **Configuration:** (Inches)
  - **Size:** 1.2” x 1.3” x 0.5”
  - **Connectors:** 2.4mm (F)

- **Configuration:** (Inches)
  - **Size:** 1.5” x 1.5” x 0.7”
  - **Connectors:** SMA (F)

- **Configuration:** (Inches)
  - **Size:** 4.5” x 1.5” x 0.4”
  - **Connectors:** SMA (F)

- **Configuration:** (Inches)
  - **Size:** 8.0” x 3.0” x 0.65”
  - **Connectors:** SMA (F)

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An Analytical Model of Quad Cable to 1 GHz: Part Two

By Kenneth S. Schneider

Ed. Note: Part one of this article published in the June 2019 issue of High Frequency Electronics.

Considering Figures 3 a-d it is evident that with respect to frequency, “f”, |ELFEXT (f, X)| dB can be partitioned into 4 segments- a Low Frequency Segment, an Intermediate Frequency Segment, a High Frequency Segment and Very High Frequency Segment. The Low Frequency Segment extends from 0 Hz to FL MHz- This exact boundary is somewhat arbitrary and loosely dependent upon the length “X.” However, it is approximately 1 MHz. It is typically characterized at short lengths- e.g. 66 m- by the presence of some resonant notches and ripples and at higher lengths by continuous convex curvature. The derivative of |ELFEXT (f, X)| dB with respect of “f” in the Low Frequency segment is certainly not constant but if it were to be “roughly” approximated it would be 10 dB per decade. The crosstalk mechanism in this segment is probably a combination of both capacitive and inductive coupling. The Intermediate Frequency Segment extends from FL MHz up to a boundary frequency of FI MHz. This boundary frequency depends “loosely” on the length, “X.” It can be approximated-for the range of lengths of interest here- at 60 MHz. Again, the derivative of |ELFEXT (f, X)| with respect of “f” in the Intermediate Frequency segment is not constant. It tends to be high at the low end of this frequency range but “then settles out” and can be well approximated by 20 dB per decade for most of this segment. It is this behavior which has been modelled in [3]. This behavior indicates that capacitive coupling dominates as the cause of the crosstalk coupling in this frequency range. The High Frequency Segment extends from FI MHz to FH MHz. Again, the boundary frequency FH MHz depends “loosely” on the length “X”- decreasing with increasing “X.” It varies from about 100 MHz to 200 MHz for the lengths of interest in the model. It can be approximated by 150 MHz. The derivative of |ELFEXT (f, X)| dB with respect of “f” in the High Frequency segment is certainly not constant but “close” to it though slowly increasing. It can be well approximated by 40 dB per decade for most of this segment. Though this “exact” value is somewhat arbitrary and just indicates a significant “slope discontinuity” in the “straight line approximations” to these segments. The Intermediate Frequency Segment and the High Frequency Segment illustrate what has been referred to as the “Dual Slope Effect.” But, as is evident from these figures this is a very simplistic-if not crude-way of describing what is clearly a very complex phenomenon. Computational experiments performed in the modelling indicate that this “slope discontinuity” is directly related to the frequency dependence of the conductivity and to the presence of the periodic twists in the cables. There are “ripples” evident at the lower lengths see for example the region between 100 MHz and 200 MHz for 66 m are due to the periodic twists as has been made clear from computational experiments. These seem to move to the high frequencies with greater loop lengths. All of this indicates a very complex interaction of different coupling mechanisms. These most likely include capacitive coupling, inductive coupling complicated by the twisting. The Very High Frequency Segment begins at FH MHz and extends upward from that to 1 GHz and beyond. Here |ELFEXT (f, X)| dB versus “f” appears to “oscillate” in an aperiodic manner often going well above 0 dB. The oscillations seem to follow the pattern like a “downward Chirp Radar
waveform—with a frequency parameter rather than a time parameter—and with a decreasing amplitude. However, this “extreme” aperiodicity is a “little deceptive” as the abscissa is logarithmic. Studies performed in developing the model indicate that this is principally caused by the aperiodic twists and to a much lesser extent by the increase in the imaginary component of the dielectric constant. Notice at the extreme right-hand side of each of the figures—close to 1 GHz. This behavior seems “to burst out again.” Computations indicate that this is “roughly” repetitive in with increasing frequency. The presence of this behavior with \(|\text{ELFEXT}|\) repeatedly going through 0 dB may well affect the cancellation of FEXT through Vectoring—which is a key processing technique used in the development of the emerging broadband technologies. Furthermore, the oscillatory behavior is like paired echo distortion. If it gives rise to “early” and “late” echoes of the FEXT this may also affect the cancellation of FEXT through Vectoring—there may be loss of synchronization of the FEXT with the direct path signals.

Clearly from considering Figure 3 a-d FL, FI and FH vary “loosely” with loop length. But, for the purposes of the continued development of the model herein they are approximated as follows:

\[
\begin{align*}
F_L & \approx 1 \text{ MHz}, \quad F_I \approx 60 \text{ MHz}. \\
F_H & \approx 150 \text{ MHz}
\end{align*}
\]  

(16)

Discussion now will be directed at the variation-of \(|\text{ELFEXT}(f, X)|\) dB with “X” at different fixed frequencies, “f.” This is illustrated by Figure 4 which covers the range of lengths which are of interest in the emerging broadband communication technologies—i.e. up to several 100 m. This is also shown for a wide range of fixed frequencies ranging from 1 MHz to 100 MHz. The range of frequencies has been limited to be less than FH MHz—the beginning of the “Very High Frequency Segment”—because variation with respect to “X” with the oscillatory behavior is really not meaningful.

Considering Figure 4, and the computational analyses underlying it indicates that at the lower lengths, “X” there is almost a linear dependence of \(|\text{ELFEXT}|\) on “X” and therefore a logarithmic dependence of \(|\text{ELFEXT}|\) dB on “X.” However, as “X” increases this logarithmic dependence of \(|\text{ELFEXT}|\) dB on “X” gives way to \(|\text{ELFEXT}|\) dB approaching a fixed asymptote—the value of which depends upon the fixed frequency. Figure 4 indicates that “the neighborhood” of this asymptote is reached generally when “X” is in the interval from 400 m to 500 m.

The almost linear dependence upon X at the lower values of “X” has been observed and expected at communica-
tion technologies which have been of interest, in the past, at the lower frequencies-below 30 MHz. It is usually readily explained as follows. If the transmission line model is considered from the point of view of “Circuit Theory” with the crosstalk effected by capacitive coupling—the dominant mechanism at these frequencies—then what you have are a continuing number of capacitors in parallel—increase with “X.” As “X” increases the number of capacitors increases and the FEXT would be expected to grow linearly with “X.” This has been noted in the technical literature. The great

Figure 3 • |ELFEXT (f, X)| dB vs frequency in Hz for a. X = 66 m, b: X = 100 m, c: X= 200 m, d: 400 m.
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Bell Telephone Laboratories engineer, G. A. Campbell noted this in the application to the twisted pair cable loops of the telephone system [8]. Work on similar but different problems has also noted this [9], [10], [11] though not in the context of twists in the cable.

Now what is very interesting in observing Figure 4 is that the “linear dependence” (logarithmic in dB) “disappears.” The variation with “X” instead appears to follow the linear dependence up to some threshold length, “X₀,” in the 400 m to 500 m interval and the for lengths X > X₀ rapidly approaches an asymptote.” This asymptotic behavior is consistent with the modeling approach obtained through simulations and reported by van den Brink [4] and extended by van den Brink, H. Verbueken, J. Maes. For purposes of continuing the modeling in the sequel the following specification will be made:

\[ X₀ = \text{400 m} \quad \text{(17)} \]

Computational experiments have been carried out with the model being developed which appear to indicate that this deviation of the dependence of \(|\text{ELFEXT}|\) dB on “X” from logarithmic to asymptotic behavior is related to the length of the twist in the Quad Cable. Figure 5 illustrates this and indicates \(|\text{ELFEXT}|\) dB versus “X” at a fixed frequency of 50 MHz for 3 different twist lengths. Note that as the twist length gets shorter and shorter then tendency to deviate from the logarithmic behavior to the asymptotic behavior gets more pronounced.

The characteristics which have been noted in the above discussion allow the following formulae to be used as a reasonable approximation to \(|\text{ELFEXT}(f, X)|\) dB which can be used for further modeling and simulation purposes. These formulae follow the trend lines indicated and for simplicity do not include the resonant effects - except for the Very High Frequency segment where the oscillatory behavior has been represented.

\[ |\text{ELFEXT}(f, X)| \text{ dB} \approx [K\text{FEXT}] \text{ dB} + \Gamma_x (f, X) \text{ dB} + \Gamma_f (f, X) \text{ dB} \quad \text{(18)} \]

Here \(\Gamma_x (X) \text{ dB}\) principally represents the dependence upon “X” and is defined by:

\[ \Gamma_x (f, X) \text{ dB} = 20 \log[X] \text{ for } X \leq X₀ \]
\[ \Gamma_x (f, X) \text{ dB} = 20 \log[X₀] \text{ for } X > X₀ \quad \text{(19)} \]

where \(X₀\) is given by (17).

\(\Gamma_f (f, X) \text{ dB}\) principally represents the dependence upon “f” and is given below with \(F_L, F_I\) and \(F_H\) given by (16):

**Low Frequency Segment**

\[ \Gamma_f (f, X) \text{ dB} = 10 \log(f) \text{ for } f \leq F_L \quad \text{(20)} \]
Intermediate Frequency Segment

\[ \Gamma_f (f, X) \text{ dB} = \Gamma (FL, X) \text{ dB} + 20 \log (f) \text{ for } FL < f \leq FL \]  
Where the first term on the right-hand side comes from (19)

High Frequency Segment

\[ \Gamma_f (f, X) \text{ dB} = \Gamma (FL, X) \text{ dB} + 40 \log (f) \text{ for } FL < f \leq FH \]  
Where the first terms on the right-hand side comes from (21).

Very High Frequency Segment

\[ f (f, X) \text{ dB} = (FH, X) \text{ dB} + A \Gamma \sin (2 \pi f \Gamma) \text{ for } f > FH \]  
Where \( A \Gamma = 40 \ e^{- (fM - 150)/100} \) and \( \lambda \Gamma = 4 \)  

\[ [K_{FEXT}] \text{ dB} = -165.6505 \]  

The value of \([K_{FEXT}]\text{ dB}\) corresponds to \(K_{FEXT} = 5.59 \times 10^{-9}\). This is higher than the value used in [3] which is \(8.80 \times 10^{-11}\). However, a difference is to be expected as [3] deals with unshielded twisted pair cables and the current modelling effort is directed at Quad Cables. As noted the above formulas are approximations. They are a simplification of quite complex behavior- this is especially true with respect to the specifications of \(A \Gamma\) and \(\lambda \Gamma\). The intent was to put in these in a form so that they can be readily applied in simulation efforts. However, they do capture the characterizations observed from the exact computational results.

Consideration is now given to the phase \(\Phi_{ik}(f, X)\) with respect to “X” and “f.” \(\Phi_{ik}(f, X)\) has not received adequate attention in modelling efforts directed at other cable types such as those presented in [3] and [6]. van den Brink does discuss it for Quad Cable in [4]- though quite tersely.

\(\Phi_{ik}(f, X)\) has been computed using the analytical approach of the mathematical development which is the basis of the model presented. Figure 6 a, b, c, d, and e illustrate \(\Phi_{ik}(f, X)\) (degrees) vs. frequency (Hz) for a range of exposure lengths “X.”

In considering the examples of the phase variation with frequency shown in Figure 6 they all have similar characteristics. The phase variation appears constant at an average value of approximately -50 degrees up until about the
Quad Cable

beginning to the Very High Frequency Segment—slightly above 100 MHz. At this point it becomes oscillatory—very similar to the |ELFEXT| dB behavior. Note again that the abscissa in Figure 6 is in logarithmic units and this deceptively makes the variation look like a decreasing period—yet this behavior is interesting. It indicates that in this Very High Frequency Segment the phase seems to oscillate between approximately 180 degrees and -180 degrees. Though this again may be deceptive because -180 degrees is effectively 180 degrees and once could say that the phase is at 180 degrees. The origin of this behavior in the Very High Frequency Segment is a subject for future study.

This parameter has been addressed for the case of Binders of Unshielded Twisted Pair cable using a novel statistical approach in [3]. However, this required the collection of a massive amount of experimental data to estimate the underlying statistical distribution. Such data is currently not available for the case of interest here—dealing with Quad Cables. With the development of the present model focused on Quad Cables a deterministic “geometric approach” is employed. It should be noted that Strobel also used a geometric approach as reported in Appendix I of [7]- which though not readily evident does have some similarities.

The geometric approach used herein rests on 3 assumptions which will be justified. However, it must be noted that this approach follows that of [3] in ignoring any frequency dependence of ‘θik ‘. This is a necessary simplification...
as it is beyond the range of issues addressed by the modelling effort presented. Assumption #1 - Initially all Quads are close packed with each Quad located on the lattice points of a diamond shaped grid. Such a grid is illustrated in Figure 7. The coordinates of the lower boundary are (1,0) ... (1,15). The coordinates of the left boundary are (0,1) ... (0,14). The coordinates of other points can be discerned from this. The diamond shaped grid is used because its symmetry mirrors the symmetry of a Quad and this is convenient for descriptive purposes.

The placement of individual Quad Cables on such a diamond grid is illustrated in Figure 8. Here 4 cables are shown. The location of each Quad is the coordinate of its center point. Thus, the location of Q-1 is the coordinate (1,1). The location of Q-2 is (2,2). Other Quad Cables will be so identified. It is to be noted that in Figure 3 the 2 Quad Cables, Q-1 and Q-2 are “adjacent”- they are as close as possible.

A configuration of 8 Quad Cables close packed on the diamond grid is illustrated in Figure 9.

The coordinates of these 8 cables- corresponding to coordinates of their center points- are given by: Q-1 (1,1), Q-2 (2,2), Q-3 (3,1), Q-4 (1,3), Q-5 (4,2), Q-6 (3,3), Q-7 (2,4), Q-8 (5,3)

The justification for this assumption is the observation of actual cable types used. Figure 10 shows photographs (obtained from a collection of photos on the Internet) actual Quad Cable Binders used for telephone loops. As indicated they are all “pressed together”- thus a close packed assumption can be justified. Placing each on the lattice point of a rectangular grid is a reasonable simplification that allows for analysis. Assumption #2 - the geometric arrangement remains the same over the entire length of the cable- or at least over the length of a segment for which the full transmission line behavior is being considered. This assumption is justified by the observation that any action that does not compromise the continuity of a cable pair should not affect the topological closeness from one end the other. In other words, a twisting of the entire Binder should not affect the closeness. Assumption #3 - While initially all Quads are close packed as time proceeds 3 principal causes will allow the distance between the Quads to increase. These causes are thermal transients- heating and cooling- naturally occurring mechanical vibrations- due to wind,
Quad Cable

rain and other weather effects- and mechanical vibrations due to vehicular traffic, construction and handling by technicians and others. Essentially, it is assumed that there will be a dilation of the close packing. There will be a slackening of the close packed configuration. This is very reminiscent of effects related to the Second Law of Thermodynamics. In a way, it may be related to the statistical approach used in [3]. However, further discussion of this is beyond the present contribution. Furthermore, this assumed dilations allow the results of the model to be applied to situations where the close packing is not rigidly carried out on a diamond grid but is limited by other physical constraints - for example requiring the individual Quads to be placed on the circumferences of concentric circles - thus increasing average distance between some.

Given these 3 Assumptions the following general points are made: FEXT is caused by capacitive imbalance between 2 pairs. When the pairs are in the same Quad this is termed “Intra-Quad FEXT.” When the pairs are in different Quads this is termed “Inter-Quad FEXT.” This capacitive imbalance itself is driven by the actual value of the capacitances between the individual wires. If this, did not exist then there would be no imbalance and no FEXT. The capacitance is expected to be maximum when the pairs are as close as possible -as in the same Quad- “Intra-Quad FEXT.” For “Inter-Quad FEXT” it is reasonable to assume that the capacitance is maximum when the corresponding pairs are adjacent on the Grid shown in the above Figure 7. This corresponds to a Euclidean Distance in Figure 7 = 1. The capacitance decreases between 2 cable pairs with the Euclidean Distance. However, the capacitance also decreases between 2 cable pairs if the area through which the Electric Flux protrudes is reduced. This may be caused by blockage if other cable pairs are between the 2 cable pairs of interest. If 2 cable pairs are adjacent, then there is no blockage. On the other hand, if 2 cable pairs are at the opposite far vertices of the square Grid shown in the above Figures then there is maximum blockage.

Let “Cadj” be the capacitance between 2 pairs which are in different Quads, but which are adjacent. Let “C” be the capacitance between 2 cable pairs of interest but each in a different Quad. Then:

\[ C = (1 + \chi) \times C_{adj} / \text{Euclidean Distance} \]  

(25)

The division by Euclidean Distance corresponding to the reduced capacitance by separation. The first factor on the right side of (25) corresponds to the “blockage.” The term “\( \chi \) will = 1 if the 2 cable pairs are adjacent and there is no blockage. This is somewhat arbitrary- another value can be chosen. But, it is not unreasonable. Otherwise will increase with Euclidean Distance. For purposes of this present model it is not unreasonable to have:

\[ \chi = \text{Euclidean Distance} \]  

(26)

Proceeding on this basis, ignoring the “1” above and substituting (16) brings:

\[ C = [C_{adj}] / [\text{Euclidean Distance}]^2 \]  

(27)

and \( C/[C_{adj}] = 1/[\text{Euclidean Distance}]^2 \)

This is “almost” the “Amplitude Offset “factor, “\( \theta_{ij} \).” What is needed is to account for the “distance dilation” associated with Assumption 3. This is done through the factor “KD” – taken to be a positive number and

\[ \theta_{ij} = 1/(K_D [\text{Euclidean Distance between “i” and “j”}])^2 \]  

(28)

\( K_D \) is taken = 2. This “dilates” the Euclidean distance. Basically, we are assuming that each of the components causing the dilation- men-
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mentioned in Assumption #3- provides a dilation with the sum totaling to "2." While this is an assumed value it is also a reasonable value. Because of mechanical constraints- such as the shield and any jacketing- the dilation must be limited-where “Euclidean Distance” refers to the “Euclidean Distance” between the separate Quads corresponding to loops “i” and “j” on the grid of Figure 6. When expressed in dB this is:

$$[\theta_{ij}] \text{ dB} = -40 \log[\text{Euclidean Distance between "i" and "j"] - 12$$

(29)

When considering a configuration of Quad Cables in a Binder- they are considered as “close packed”- with each Quad covering an empty “diamond” shape within the grid. For purposes of this model when determining the actual placement of the Quad Cables on the grid shown in Figure 6- this should be done in the following way: Place the first Quad at the lattice point given by the coordinates (1, 1). For each additional Quad- place it at that currently empty lattice point with coordinates so that the Euclidean distance between it and (1, 1) is at a minimum. The empty lattice point must allow the placement of a Quad so that it is fully within the lattice. By way of example, the coordinate (2, 2) would be allowed but not (0, 3). The empty lattice point must be such that the Quad which has it as its center does not overlap any other Quad. By way of example the coordinate (2, 2) would be allowed but not (1, 2). This should always be done in this manner to allow consistency when computations are carried out.

For the example of the close packed 8 Quad Cables shown in Figure 8 it is interesting to compute the range of the Amplitude Offset. Note: this corresponds to 16 pairs with 2 pairs per Quad Cable. The greatest offset would be between cables Q-1 and Q-8. The Euclidean Distance here would be 20 $\sqrt{5}$ or 4.47. This corresponds to an Amplitude Offset of 26 dB. This is in the same range of values as obtained with the ATIS model [3] though a little less. But, this is to be expected. We are dealing here with 8 Quads- 16 cable pairs not the 25 cable pairs of the ATIS Model Binder. This also is representative of the measured data provided in [5]. Using the procedure described above an example Amplitude Offset Matrix $[\theta_{ij}] \text{ dB}$ corresponding to 4 Quad Cables- 8 pairs- is shown in Table 2 where each row/column number corresponds to a Pair number. These 8 pairs point must be such that the Quad which has it as its center does not overlap any other Quad. By way of example the coordinate (2, 2) would be allowed but not (1, 2). This should always be done in this manner to allow consistency when computations are carried out.

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It is worthwhile to compare the values in Table 2 with comparable values obtained by the statistical approach used in [3]. The upper left 5 x 5 submatrix of the Amplitude Offset Matrix in [3] is provided in Table 5- though this corresponded to Unshielded Twisted Pair cables not Quad Cables. This Amplitude Offset Matrix in [3] is essentially “slightly asymmetric”- though there is a procedure for converting it to a symmetric matrix. Nonetheless, it is best to consider the “slightly asymmetric” version. Comparing the matrices in Table 2 and Table 3 it is evident that the values are in the same general range-though with those of Table 5 trending higher than those of Table 2. This provides credibility that both approaches are coming up with reasonable- though not identical- results given limits to the essential knowledge of the problem.

It is also worthwhile noting that the average Amplitude Offset in Table 4 is -23.5417 dB.

“$\Psi_{ik}$ “

Using the approximation for $\Phi_{ik} (f, X)$ given in degrees- this can be converted to radians by multiplying by $\pi/180$ to obtain $\Phi_{Rik} (f, X)$. From this is obtained $\Psi_{ik} = d + \Phi_{Rik} (f, X)$, where $\beta$ is approximated by (Group Delay)$f$ with “Group Delay” given a constant in (5).

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Table 2 • Example $[\theta_{ij}] \text{ dB}$ for 4 Quad Cables- 8 Pairs
3. MODEL COMPARISON WITH EXPERIMENTAL MEASUREMENTS

In concluding, a brief comparison is made of the predictions of the theoretical model to experimental measurements made of an actual PE4D-ALT used by Swisscom [12]. In the interest of conciseness attention will only be directed at the dependence of $|\text{ELFEXT}|$ dB on frequency. Comparisons with respect the dependence of $|\text{ELFEXT}|$ on exposure length, with respect to the phase of ELFEXT, direct path attenuation and Group Delay, and the Amplitude Offset are of interest but will not be dealt with. Figure 11 shows an intra-quad ELFEXT measurement of a PE4D-ALT cable of 66m length consisting of 10 quads with wire diameter of 0.6mm. The measurement is compared with the ELFEXT calculation based on the parameter values assumed in this paper. Calculated and measured curves show a great similarity in shape but are not completely aligned e.g. the dips do not coincide exactly. This can be explained by the fact that the model parameter used were not fitted with the measurements. This would have to be done in a next step to get optimized parameter values. In addition, Figure 11 shows also the four-segment model developed in this paper, which was explicitly fitted to the measurement data shown in the same figure.

Acknowledgements

Mr. Marcel Reitmann of Swisscom was very helpful in providing experimental measurements for validating the analytical model. Mr. Seth Stowell and Dr. Knut Kongelbeck assisted with carrying out difficult computational experiments. Interaction with Professor (Emeritus) Dante Youla (PINY- New York University) was of great value. He pro-

| -13.6823 | -15.1213 | -10.6057 | -16.8391 | 0        |

Table 3 • Submatrix of $[\theta_{ij}]$ dB for twisted pair cables in [3]

Figure 11 • Swisscom intra-quad $|\text{ELFEXT}|$ measurement of PE4D-ALT 10x4x0.6mm cable of 66m length vs. calculation and model.
Quad Cable

vided the theoretical foundation for this modelling effort and invaluable insight into the many issues arising as it was carried out. Professor (Emeritus) John Murray (SUNY-Stonybrook) aided in the expansion of this theoretical foundation. The text and illustration editing provided by Mrs. Victoria Twomey was invaluable.

References

13. TR-285 “Broadband Copper Cable Models,” Table 3., Issue 1 Amendment 1, March 2017.

About the Author

Kenneth S. Schneider is the CEO and founder of Telebyte, Inc., which is focused on the development, manufacture and marketing of test equipment for the broadband telecommunications market. He received the BS, M. Eng. (Elect) and PhD degrees all from Cornell University. Dr. Schneider has been active in the development of communications technology throughout his career. This included work as a member of technical staff at Hughes Aircraft Company, M.I.T. Lincoln Laboratory, and Network Analysis Corporation. He has also taught communication theory at the Polytechnic Institute of New York. He has published more than 100 technical papers, holds three patents, and is the recipient of the IEEE (Long Island Section) Harold Wheeler award.
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<td>DC-10 GHz</td>
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