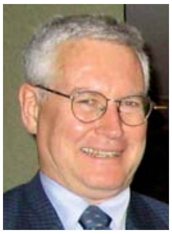

EMC History

Dan Hoolihan, Associate Editor
Chair of the EMC 50th Anniversary Committee and the History Committee

We are pleased to publish in this issue an article contributed by one of the most distinguished and accomplished people in the IEEE EMC Society – Clayton R. Paul.

As many of you know, Clayton has won numerous IEEE and EMC Society Awards including the 2007 IEEE Undergraduate Teaching Award, the prestigious 2005 IEEE Electromagnetics Award, the EMC Society's Richard R. Stoddart Award for Outstanding Performance (twice – once in 1993 and a second time in 1996), and many other Awards. He is also known for his excellent textbook, *Introduction to Electromagnetic Compatibility*, recently published as a Second Edition.

One of the comments in Clayton's contribution that resonated with me was his remark about "my entry into a career in EMC happened much like many of my colleagues." That is, by accident, or inadvertently! This was similar to my experience; believe it or not, I actually started in EMC (although most of us called it RFI for Radio Frequency Interference) a year before Clayton Paul. I graduated with a Master's Degree in Physics in 1969 and went to work for Control Data Corporation in their RFI Lab. I barely knew what RFI was when I started. Most of my colleagues at Control Data referred to the RFI lab and the men who worked in it as the "Noise Boys." We were specialists in "electrical noise" problems and there were many susceptibility problems in those days and, hardly, anyone worried about emission issues with commercial products.

However, the military products were a different story and I began my career by making MIL-STD-461 measurements in a shielded room with no anechoic material on the walls or ceiling. We used instruments such as the Singer (Empire Devices) NF-105 Receiver (below 1000 MHz) and its companion receiver, the NF-112 (above 1000 MHz). These were hand-tunable devices with plug-in modules that covered a portion of the frequency range that needed to be surveyed to satisfy the military specification. The data was taken by hand and then plotted by hand against the allowed limits. It was tedious, to say the least.

Clayton Paul and I first got to know one another back in the 1970s when, as part of a military contract, Control Data wrote some technical documentation in the EMC area. Clayton was hired by the military to review our publications and we communicated back and forth on some technical issues relative to the technical guidance documents that Control Data generated. And, then in the 1980s, we begin to run into one another at the annual IEEE EMC Symposium and we became "friends through EMC." When I was operating the company I co-founded (Amador Corporation), he invited us to submit a photo of our anechoic chamber for the first edition of his textbook. We were pleased to do that and you can find that picture on page 61 of his First Edition of *Introduction to Electromagnetic Compatibility*.

I agree with many of the sentiments expressed by Clayton in his article; I especially agreed with his remarks about how EMC technology has changed tremendously in the past 38 years. We are confident that it will continue to change, yet, the future developments will always build on the firm foundation that has been built by the pioneers and those who followed in the EMC Society. Enjoy the Clayton Paul article and make sure you come to Hawaii to see the historical test equipment display that will be part of our Society's 50th Anniversary Celebration!

Celebrating Our Past; Preparing for the Future

Clayton R. Paul, Life Fellow, IEEE

This year we celebrate the 50th anniversary of the IEEE EMC Society. To commemorate this event, I wrote this article with two objectives in mind. The first is to remind us of how rapidly the practice of EMC has evolved in a very short time. The vast majority of those now in this profession are relatively new to it and have little or no understanding of what EMC was like even as recently as twenty years ago. It is important for us to remember how much we have progressed in this discipline. This review will be given in the context of the author's experience in EMC over some 35 years. The second objective is to discuss some of the looming problems to which EMC engineers must adapt. Rapid evolution of digital technology will mean that we must adopt new and more efficient analysis methods and tools in order to handle future EMC designs. Rules of thumb and previously used solution concepts are rapidly becoming incapable of handling the problems we will face. To revise our "EMC design intuition" in order to handle those future challenges, we must be willing to use the powerful computer-aided analysis and design software tools that are becoming available.

A REMINDER OF THE RAPID EVOLUTION OF THE PRACTICE OF EMC THROUGH THE AUTHOR'S PERSPECTIVE

It is important that we periodically examine our history in order to appreciate the progression of our ability to handle EMC design challenges. Those of us who have been involved in EMC for many years tend to forget that the majority of our colleagues are relatively new to the profession. Hence they may not appreciate the fact that our understanding of EMC phenomena and the tools available for solving these problems were dramatically different in the earlier years. For example, powerful desktop personal computers having clock speeds in excess of 1GHz have not always been available. The author has a somewhat unique perspective of EMC having served both in academia on an Electrical Engineering faculty where EMC was virtually unheard of and also having taken part in military and commercial EMC design. Now, due to a number of universities offering an EMC course in their undergraduate preparation, many electrical engineering graduates select EMC as a career rather than the previous practice of being "drafted" into the EMC department of their company.

I began work in EMC in 1970 as a post-doctoral student at Purdue University working with the Rome Air Development Center (RADC) at Griffiss AFB, NY. My entry into a career in EMC happened much like many of my colleagues. When I graduated from Purdue in 1970 with a PhD in Electrical Engineering (EE), it was clear to me that I wanted a career as a teacher in a university. However, the job market for these positions was not good in that year. My doctoral professor heard about my difficulty in obtaining a suitable faculty position and asked if I wanted a postdoctoral fellowship for a year to wait until the job market improved. Of course I said 'yes' without inquiring about the topic of the fellowship. He said, as he walked away, "It's in Electromagnetic Compatibility." My PhD dissertation and training was in Linear Systems and Automatic Controls. Although electromagnetics was not at the top of my list of preferred subjects in EE, this turned out to be the turning point in my career. At that time, the primary EMC problems were with interference between antennas located on the same platform. Crosstalk was a mild problem and primarily involved wiring in cables. Printed circuit boards (PCBs) were not as pervasive at that time. I was fortunate to begin work with some of the giants in electromagnetics (such as Roger Harrington, Bud Adams and Jose Perini), many of whom were on the faculty of Syracuse University. They were interested in EMC problems involving antennas so I decided to tackle the issue of crosstalk in cables. I was fortunate to work at RADC for Jake Scherer and Gerry Capraro, and to also collaborate with Andy Drozd and John Norgard in those early years. Solving and modeling crosstalk problems in cables was my main focus until around 1984. The EMC standards that we dealt with were MIL-STD-461 and MIL-STD-6051D.

I know that it is difficult for many of those who are relatively "new" to the EMC profession to comprehend what it was like in a world without powerful desktop personal computers (PCs) having clock speeds above 1 GHz. Perhaps even harder to understand is the fact that we had no sophisticated, commercially-available software packages for computation or data plotting (you had to write your own software). Excel, Matlab, etc. were not in existence; plotting of data consisted of ridiculously hard-to-comprehend line printer plots using asterisks to denote the data. None of the word-processing software packages we have today were in existence. Typing technical text was done by a secretary using a typewriter such as the IBM Selectric. If you wanted to add a paragraph to what you had written and which the secretary had already typed, it was necessary to literally "cut and paste" or retype the entire document. Needless to say this was time-consuming and caused some hard feelings with the secretary.

In 1970, there were no personal computers, and the large mainframe computers were not even as capable as today's PCs. I recall in 1968 another graduate student and I obtained permission to have the IBM 7094 main campus computer at Purdue University devoted to our use in summing a long series during the early morning hours of 3AM to 4AM. We had the entire main memory of that computer at our personal disposal: all 64k of it! Hence numerical computation and modeling that we used to aid the understanding of EMC phenomena was very limited. I can also remember accessing a main frame computer in 1971 using a teletypewriter that used a punch tape to record and input the program. Around 1971, when I joined the faculty of the University of Kentucky, the main campus computer was an IBM 360. It was accessed using punch cards. The holes in the IBM program cards were punched using a key punch. You carried a large (very heavy) box containing the punch cards for your program to the computing center, loaded them into a card reader and waited overnight for the mainframe computer to run your program. (Imagine today carrying boxes of cards, which you dared not drop, containing the Matlab program to the computing center and loading them through a card reader in order to run that program to analyze a problem!) The next morning, when you went to pick up the printout of the results, you invariably learned that you had made a typing mistake. You then had to retype the erroneous program card using a key punch to re-punch the card, reload the box of cards into the card reader, and wait again overnight to see the results. It is somewhat remarkable that we ever got anything done at that slow rate of progress. There was only one video display unit in the computing center (and in fact on the entire campus) that displayed your position in the queue. Any programs you wished to run on that computer had a default memory allocation for use of 128k. If you needed more memory, which I did in order to invert 50×50 matrices, you had to request, say, 256k on the job card. When your program was read off the punch cards, you watched the VDU as your place in the queue went to "the end of the line" because of your request for "excess" memory allocation. Other users who had already loaded their small programs and who were also watching the VDU must have wondered, "Why does that idiot need that much memory?" Calculators that could perform addition, subtraction, multiplication and division as well as compute a square root were just becoming available. A Hewlett-Packard calculator that could perform only these computations cost around $400 U.S. In spite of these limitations (which we didn't know were limitations back then), EMC had already been established as an important discipline for some 20 years prior to this!

Around 1980, PCs were appearing on the market but these were very slow due to processors having clock frequencies below 10MHz and no hard drives. My first IBM PC in 1983 had an 8086 processor with a clock frequency of 6 MHz and two floppy drives (no "hard drive"). One had to load, manually by way of the "A" floppy drive, any program to memory.

In 1979, the FCC announced the imposition of mandatory radiated and conducted emission regulations on "digital" devices. Prior to that, a relatively small core of EMC professionals [such as my close friend, the late Don Bush at IBM Information Products Division (now Lexmark International) in Lexington, KY] had already been involved in EMC since the early 1950s. But the digital electronics manufacturers had voluntarily complied with their own in-house regulations prior to that as a matter of quality control. Now the matter was no longer voluntary. Digital products destined for sale in Europe had already been subject to mandatory regulations limiting radiated and conducted emissions via CISPR 22 for many years prior to the FCC rule. After the FCC put these EMC requirements into law, we saw producers of "digital" electronic devices giving more importance in their companies to the topic of EMC. Where companies had only one or two "EMC engineers" on the payroll before, we now saw them actually forming "EMC laboratories". Hence, there arose increased pressure from the electronics industry on colleges and universities to produce more electrical engineers who had some competence in the EMC area rather than their previous practice of "recruiting" their employees to serve in the EMC group.

In 1979, I was fortunate to meet and form a lifelong friendship with Henry Ott. We met at the IEEE EMC Symposium in San Diego and formed the EMC Society's Education Committee. Henry was "elected" president and I was "elected" secretary. I voted for Henry and he voted for me. (I think that was how the vote went.) I sat there and took notes as Henry talked. Partly as a result of Henry's urging, I put together one of the first university courses in EMC at the University of Kentucky around 1981.

In 1984, I made a career choice that had the most important impact on my career of any other decision before or after. Don Bush (then the head of the IBM EMC lab in Lexington, KY) suggested that I take a year sabbatical and work in his lab. In that year IBM was working on their first (as yet unannounced) electronic typewriters: the Wheelwriter and the Quietwriter. Prior to that, their famous and only typewriter was the Selectric, which was mainly mechanical with the ubiquitous rotary ball for printing. (A later design gave it a 1MHz memory in a "side car".) The Wheelwriter and the Quietwriter were quantum leaps in technology over the Selectric. The Quietwriter used a revolutionary resistive-ribbon technology where the fonts were made electronically, and the letters were literally melted onto the paper. Gone was the need for "snopake" correction fluid; erasure was simply a matter of reversing the process and lifting the type off the page. I was told that tests at a FBI laboratory were not able to determine what had been typed on the page. All this powerful printing capability required very advanced processing power in the electronics. The Quietwriter used a total of six 8051 processors each running at a "blinding" speed of 12 MHz! Remember, this was in 1984, only 23 years ago. It was during that year that I had the good fortune to work with Keith Hardin who later became my doctoral student. Keith was a member of the group that designed the Quietwriter, so he "inherited the privilege" of being assigned to guide it through EMC qualification. Keith and two of his colleagues proceeded to the EMC lab with the prototype. But after seeing firsthand the mysteries of EMC, the other two wandered off for lunch one day and never returned. But Keith, who had a gift for electronics, remained to guide the Quietwriter through the qualification process.

During that year I met another gentleman who also became a close friend. He was and still is the chief technician in that EMC lab—Steve Parker. Working in the EMC lab at IBM that year literally changed my life professionally and personally. I had the pleasure and privilege to work with some of the most capable engineers I have ever worked with and who turned out to be lifelong friends. We were constantly learning and beginning to understand new and seemingly mysterious things about electromagnetics such as common-mode currents. But keep in mind that the highest processor frequency in this product was only 12 MHz! Even so, the EMC problems we solved were very difficult back then. Today's digital products have speeds over 1GHz: an increase of almost 40dB! So we have come a very long way in our ability to solve EMC problems in the course of design.

I have always thought that it is vitally important to know our heritage. At the risk of talking about my experience here, I have tried in the foregoing to convey an appreciation of our "EMC heritage" to those who are new to the profession. In my classroom I emphasize the history of the electrical engineering profession by explaining how our scientific laws were developed in the 1800's using only very rudimentary experimental apparatus. There were no digitally controlled vector voltmeters or spectrum analyzers; the early scientists had to build their test equipment. In fact, current through wires could not be pro-

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duced until Volta constructed the first battery around the turn of the century in 1800. I tell them how Michael Faraday discovered his monumental law using the crudest of measurement equipment (by today's standards), yet it has stood unchanged for almost 150 years! What an incredible testament to his ability to perceive what his experiment was telling him.

PREPARING FOR THE FUTURE

Today one can purchase a PC having enormous computing power with clocks exceeding 3 GHz and virtually unlimited memory. (These make the mainframe computers I used in the 1970s look like an abacus board.) The spectral content of the electromagnetic signals in today's digital electronics have significant levels at frequencies exceeding 20 GHz! The demand for processing power will continue to drive our quest for faster digital devices and increased memory storage. Enormous amounts of data and information are already being displayed on VDUs, and the demand for more will without doubt continue to steadily increase. Additionally, the limits in the EMC regulations are not going to be made less stringent just because we tell the regulatory agencies that compliance is becoming increasingly more difficult.

So as the spectral content of signals in digital products increases, there is need to adopt new and more productive ways to analyze and solve EMC problems. First, we must understand the fundamental concept of electrical dimensions of our physical systems. Electrical dimensions are physical dimensions in wavelengths. For example, a wavelength in free space (air) is 1 meter at 300MHz. Increased frequencies result in shorter wavelengths. So a wavelength in air at 3GHz is 10cm or about 4 inches. A wavelength of the fifth harmonic of a 3GHz clock, 15GHz, is 2cm or about 3/4 of an inch. The other fundamental concept is that the familiar lumped-circuit analysis methods and Kirchhoff's voltage and current laws that we are accustomed to using to analyze circuits do not work for typical circuits at these frequencies. In order for these lumped-circuit notions to be applicable, the maximum circuit dimensions must be less than 1/10-1/100 of a wavelength at the frequency of excitation of the circuit. For example, suppose a printed circuit board (PCB) has some lands that are 2 inches long or about 5cm. These will be 1/10 of a wavelength (in air) at a frequency of approximately 600MHz and 1/100 of a wavelength at 60MHz. Therefore, if the signals carried by these 2 inch (5cm) lands exceed, say, 100MHz, then applying lumped-circuit analysis methods will give erroneous and misleading results. Hence the enormous background of EMC intuition and solution methods we have that were obtained from "low-frequency" analysis techniques are not going to work in the products of the future. These are not pleasant thoughts but the consequences are inevitable.

Some of the new ways of visualizing and understanding these unfamiliar phenomena can be handled incrementally. An example is to begin thinking of signal conductors as transmission lines which is what they are becoming as the frequencies increase steadily (the PC boards are not getting smaller but the wavelengths are). But this is only a temporary stopgap. If we are going to remain successful in EMC design, we must begin using the revolutionary numerical modeling tools that are being developed. This powerful software can tell us the "truth" about what is happening in our products by solving Maxwell's equations in three dimensions (3D). Additionally, these tools have sophisticated means of displaying this information thereby aiding our visualization of the fields and phenomena that we heretofore could not "see", making it easier to replace our low-frequency intuition with high-frequency intuition (for electrically small circuit dimensions).

EMC has always had and will continue to have a prominent measurement component to verify compliance with the regulatory requirements. This is becoming increasingly difficult to accomplish as the signal spectral content of our digital products continues to steadily increase. Accurate measurements in the GHz frequency range become more difficult to achieve than was the case for spectral content in the middle MHz frequency range (as was the predominant case only several years ago). So the problem of measurement for verification of regulatory compliance (and for diagnostic purposes) will become increasingly difficult.

This brings me to my final observation that there are two seemingly distinct groups emerging in our EMC community: those who are concentrated in the measurement and standards area and those involved in numerical modeling. Both groups have equally valuable contributions to make to the field of EMC so we must begin fostering communication between the two groups if we are to conquer these increasingly difficult high-frequency problems. If we work together, respecting and sharing each other's talents, we can multiply our success in resolving the high-frequency EMC problems that will dominate the future of EMC.

Biography

Clayton R. Paul was born in Macon, GA on September 6, 1941. He received the B.S. degree from The Citadel, Charleston, SC, in 1963, the M.S. degree from Georgia Institute of Technology, Atlanta, GA, in 1964, and the Ph.D. degree from Purdue University, Lafayette, IN, in 1970, all in electrical engineering. He is emeritus professor of electrical engineering at the University of Kentucky where he was a member of the faculty in the department of electrical engineering for 27 years. He is currently the Sam Nunn Eminent Professor of Aerospace Engineering and Professor of Electrical and Computer Engineering in the department of electrical and computer engineering at Mercer University in Macon, GA. He is the author of numerous textbooks on electrical engineering subjects, and has published numerous technical papers, the majority of which are in his primary research area of electromagnetic compatibility (EMC) of electronic systems. From 1970 to 1984, he conducted extensive research for the US Air Force in modeling crosstalk in multiconductor transmission lines and printed circuit boards. From 1984 to 1990, he served as a consultant to the IBM corporation, in the area of product EMC design. Dr. Paul is a Fellow of the Institute of Electrical and Electronics Engineers (IEEE) and is an Honorary Life Member of the IEEE EMC Society. He received the 2005 IEEE Electromagnetics Award "for excellence in the advancement of electromagnetic theory towards solving crosstalk problems in transmission lines and cable assemblies." **EMC**