COST-EFFECTIVE
Electromagnetic Compatibility
ANALYSIS, DESIGN AND MANAGEMENT

19 - 20 April 2001, York Hotel, Singapore

AGENDA – 19th April 2001

8.30 a.m. – 9.00 a.m. **Registration**

9.00 a.m. – 9.10 a.m. **Opening Address**
by A/Prof K H LEE, Director of Research, IHPC

9.10 a.m. – 10.00 a.m. **EMC - An Overview**
by A/Prof See Kye Yak, NTU

- The concern of EMC
- Introduction of EMI regulations
- Common EMI measurement units

10.00 a.m. – 10.30 a.m. **Tea Break**

10.30 a.m. - 12.30 p.m. **Controlling Conducted and Radiated EMI by Design**
by A/Prof See Kye Yak

Part I-Conducted EMI
- How conducted EMI is generated?
- Concept of conduction modes
- Power line EMI filter design
- Conducted EMI diagnosis

Case studies and experimental results

12.30 p.m. – 1.30 p.m. **Lunch**

1.30 p.m. - 3.00 p.m. **EMC Modeling and Simulation**
by Dr Lee Erping, IHPC

- EMC/EMI problems in electronic designs
- Electromagnetic modeling techniques
- Preparation for modeling
- Creating EMI/EMC models

3.00 p.m. – 3.30 p.m. **Tea Break**

3.30 p.m. - 5.00 p.m. **EMI Reduction by Simulation**
by Dr Lee Erping, IHPC

- Signal integrity at high speed PCB design
- Component Modelling, IBIS models
- EMI simulation

5.00 p.m. **End of Day One**

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9.00 a.m. – 10.00 a.m. **Controlling Conducted and Radiated EMI by Design**
by A/Prof See Kye Yak, NTU

Part II-Radiated EMI
- The radiation mechanism
- Concept of radiation modes
- Power supply decoupling for PCB
- PCB layout consideration
- Case studies and experimental results

10.00 a.m. – 10.30 a.m. **Tea Break**

10.30 a.m. – 12.00 p.m. **Controlling Conducted and Radiated EMI by Design (cont'd)**
by A/Prof See Kye Yak, NTU

12.00 p.m. – 1.00 p.m. **Lunch**

1.00 p.m. - 3.00 p.m. **EMC Testing**
by Chow Wee Sing, CET

- Necessity for EMC tests
- EMC Test Facilities (OATS, Semi-anechoic chamber, TEM)
- EMC test standards
- EMC test methodology
- EMC test environment and equipment
- System level EMC testing considerations

3.00 p.m. – 3.30 p.m. **Tea break**

3.30 p.m. – 5.00 p.m. **EMC Management for Transit and Traffic Projects**
by Dr Sam Chan, LTA

- Key EMC management principles for transit and traffic projects
- Key EMC activities at each project stage
- EMC documentation
- Implementation Issues
- The Way Forward

5.00 p.m. **Closing Remarks**

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19 - 20 April 2001 (Thursday and Friday)

Course Synopsis

Electromagnetic Compatibility (EMC) has become a major concern for electronic and electrical industry due to rapid advancements in microelectronics and its wide applications. Minimizing electromagnetic interference (EMI) and coupling within the circuits, system and between the systems is a key design aspect in electronic and electrical engineering and even packaging engineering. Most design engineers are competent in designing a circuit or system to perform a specific function but lack the necessary knowledge for designing that circuit or system to meet the required EMI specifications. Although some quick "hard-fixes" to a product at the final design stage may help it to comply with the required EMI limits, these under-the-pressure remedies can be very expensive to implement. On the other hand, increasing cost competitiveness in the electronic market has forced the manufacturers worldwide to look into cost-effective EMI solutions.

The short course aims to fill the "EMI knowledge gap" with concise, practical treatments of how EMI is generated by an electronic product, and how to suppress it through proper designs at the initial design stage, without incurring unnecessary additional costs. In view of a diverse engineering background of the course participants, the short course covers the following areas so that all participants can benefit from the course.

- **EMC design at the circuit level**

  This is to provide insights on how EMI is generated from bad PCB layout practice and poor design of switched-mode power supplies. Many case studies and experimental results will be shown to demonstrate how to solve EMI problems effectively without adding costs to the product.

- **EMC modeling and simulation**

  This is to demonstrate the use of new EMC analysis and design methodologies by applying innovative modeling and simulation techniques.

- **EMC design at the system level**

  This is to provide project engineers/managers and consultants with system-level EMC design and management concept so that the final systems will not be malfunction due to EMI problems. This is suitable for managers and contractors who are handling large-scale projects such as MRT/LRT, telecommunication and military projects.

- **EMC testing**

  This is to expose the participants with current and new EMC testing facilities and test methodologies.

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ANALYSIS, DESIGN AND MANAGEMENT

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Speaker's Bio-Data
(in order of appearance)

Dr See Kye Yak received the B. Eng. degree from National University of Singapore, in 1986, and the Ph. D. degree from Imperial College of Science, Technology and Medicine, University of London, England, in 1997. From 1986 to 1991, he worked as an EMC Engineer at the EMC Centre, Singapore Technologies Electronics Ltd. From 1991 to 1993, he was a Lead Design Engineer with ASTEC Custom Power Pte. Ltd. He is currently an Associate Professor in the School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore. His experiences include EMC testing and compliance, EMC design, numerical methods in EMC, EMI reduction techniques for electronic products.

He is a senior member of Institute of Electrical and Electronic Engineers, USA. He is also a member of Applied Computational Electromagnetics Society, USA. He has been an active Technical Assessor for EMC Laboratory Accreditation Scheme, Singapore Accreditation Council since 1997.

Dr Lee Erping received his PhD from Sheffield, UK, in 1992. He has been a Research Fellow and lecturer with Department of Electrical and Electronic Engineering at Sheffield Hallam University from 1988 to 1992, Senior R&D Engineer with Singapore Institute of Standard and Industrial Research from 1993-1996. Prior joining IHPC, he was working with MRT North East Line project on EMC analysis and Management. He is currently the Division Manager of Electromagnetics at the Institute of High Performance Computing(IHPC) where he is responsible for project management and research in high speed electronic design, EMC computational modeling and simulation, EMC control and management.

Dr Lee has many years of research and industrial experiences in EMC control and design, computational electromagnetics, high speed electronic design and project management. He has served as a Co-Chairman and session chairman for a number of international conferences. He has conducted public seminars and in-house seminars on EMI in high speed electronic design and EMC simulation.

Mr Chow Wee Sing received his BEng in electrical and electronic engineering in 1991 and MSC in industrial system engineering in 1998 from NUS. Since graduated, he has being worked with ST electronic engineering LTd as project engineer, senior project engineer in EMC testing and design. He is currently the Manager of EMC centre in CET technologies Pte Ltd. He has been involved in EMC testing, design and management for various products both military and commercial applications, system integration and pre- and post-installation EMI measurements.

Dr Sam Chan obtained his BSc degree and Ph.D. in Electronic and Electrical Engineering from University of Birmingham, U.K. in 1985 and 1988 respectively. He is currently Manager of System Integration Department at LTA. His main areas of work have been in systems engineering and integration, EMC and interface management. He has been working in the above areas on a number of railway and transit projects for British Railways, London Underground, Hong Kong Mass Transit Railway Corporation from 1988 before joining LTA in June, 1997. Since then, he has also been involved in transit and traffic related projects being undertaken by LTA.'

Cost-Effective Electromagnetic Compatibility

Analysis, Design and Management

19-20 April 2001
York Hotel, Singapore

Course Contents

- EMC Design : See Kye Yak (NTU)
- EMC Simulation: Lee Erping (IHPC)
- EMC Testing: Chow Wee Sing (CET)
- EMC Management: Sam Chan (LTA)

An Overview of Electromagnetic Compatibility

Associate Professor See Kye Yak
School of Electrical and Electronic Engineering
Nanyang Technological University

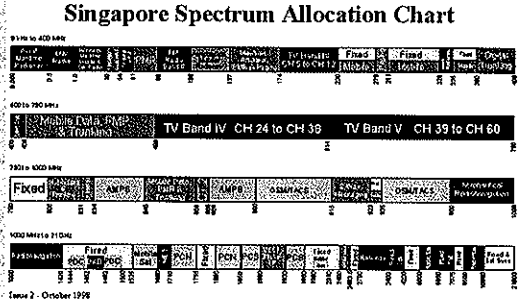
Electromagnetic Compatibility

The ability of a device, equipment or system to function satisfactorily in its intended electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in that environment

History of RFI/EMI

- **1901:** first wireless transmission by Marconi
- **1920s:** RFI to radio receivers due to other transmitters
- **1930s:** RFI to radio receivers due to motors, electric railroad and electric signs
- **1940s:** more RFI problems reported due to heavy usage of radio equipment and electronics in military services
- **1950s:** invention of BJT
- **1960s:** development of ICs
- **1970s:** development of microprocessor chips
- **1980s:** widespread use of digital control
- **1990s:** explosive growth of wireless communications

Singapore Spectrum Allocation Chart



Degrees of EMI Problems

- Nuisance

  The EMI event usually lasts for a short duration and causes no damage
- Catastrophic

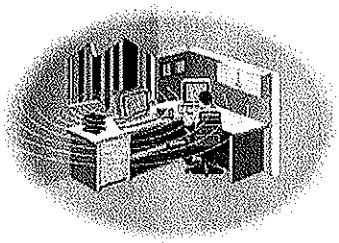
  The EMI event leads to serious consequences such as loss of life or extensive damage
- Intermediate

  Most EMI events are fall between nuisance and catastrophic

TV Image when a Nearby Electric Motor Turn On



Computer Monitor in Close Proximity to Electrical Power Riser



Malfunction of Hospital Devices

Canadian Medical Association Journal (1996):

EMI from sources such as TV transmitters, police radios and cellular phones can cause monitors and other medical devices to malfunction, says Bernard Segal, principal investigator of the McGill University Biomedical Engineering Group on Electromagnetic Compatibility

Interference With Powered Wheelchairs

Report from University of Pennsylvania (1994):

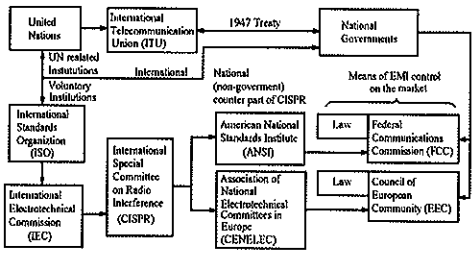
A compliant of possible EMI with motorized wheelchairs was reported in June 1992. As a result, different models of wheelchairs were tested in the EMC laboratories. Several brands of power driven wheelchairs and scooters were susceptible to interference at various radio frequencies. In some tests, the brakes released. In others, the wheels moved uncontrollably. Sometimes both occurred at once.

Concerns About Passengers' Electronics

Aviation Week and Space Technology (1996):

From the 33 reports direct to International Air Transport Association (IATA). 21 incidents related to laptop computers and only 2 to cellular phones. Navigation systems were affected in 26 of those incidents; fuel systems, warning lights and propulsion reported one incident each. Rough correlation of suspect with effect by turning the suspect device on and off was found in 14 cases and no correlation in 13 cases.

National Lawmaking Process



Electrical Dimensions

Electrical dimensions are measured in wavelength:

$$\lambda = \frac{v}{f} \quad \text{m}$$

v is the velocity of propagation of EM wave in free space (3×10^8 m/s)

f is the frequency of the signal concerned

Wavelengths at Different Frequency (in Air)

Frequency	Wavelength
50 Hz	6,000 km
3 kHz	100 km
30 kHz	10 km
300 kHz	1 km
3 MHz	100 m
30 MHz	10 m
300 MHz	1 m
3 GHz	10 cm
30 GHz	1 cm

EMI Analysis Methods/Tools

- Electrically small circuits
  - Physical dimension < 0.1 λ
  - KVL, KCL and lumped circuit modeling can be used for analysis
- Electrically large circuits
  - Physical dimension > 0.1 λ
  - Full-wave approach is the only method for analysis

Common EMI Units in Decibel

- Conducted EMI units

$$dB\mu V \equiv 20\log\left(\frac{\text{Volts}}{1\mu V}\right)$$

$$dB\mu A \equiv 20\log\left(\frac{\text{Amps}}{1\mu A}\right)$$

- Radiated EMI units

$$dB\mu V/m \equiv 20\log\left(\frac{V/m}{1\mu V/m}\right)$$

$$dB\mu A/m \equiv 20\log\left(\frac{A/m}{1\mu A/m}\right)$$

Linear to Decibel Conversion

- Example 1: Express 23 mV in unit of dBμV

$$23\,mV = 23\times10^{3}\,\mu V$$

$$20\log\frac{23\times10^{3}\,\mu V}{1\mu V} = 87.2\,dB\mu V$$

- Example 2: Express 200 V/m in unit of dBμV/m

$$200\,V/m = 200\times10^{6}\,\mu V/m$$

$$20\log\frac{200\times10^{6}\,\mu V/m}{1\,\mu V/m} = 166\,dB\mu V/m$$

Application Notes

ScanEM-C CTK015 Probes and Signal Integrity **AN103**

Problem

High-speed digital circuits often behave more like analog circuits. Instead of usual "0s" and "1s" the electrical signals exhibit such artifacts as ringing, overshoots, undershoots, ground bounce and a plethora of other non-digital characteristics. The reason for such behavior is that at high frequencies parameters like distributed capacitance and inductance of traces, mismatched impedances, etc. – things that are normally considered a worry of an RF Engineer – are becoming harsh reality for a Digital Engineer. If a clock in a system is unhurried by today's standards 27MHz, just keep in mind that radio remote-controlled cars use this frequency for their RF communication. 49MHz is a carrier frequency for a typical cordless telephone and walkie-talkies and so on. More and more high-speed digital systems invade frequency ranges previously occupied by RF transmission.

However, the high-speed clock frequency by itself is often a secondary problem to the less-obvious corollary of much shorter rise and fall times provided by the ICs. 1.5nS-rise and fall times are not unusual occurrences on today's PCB assemblies. However glamorous in the digital world, 1.5nS transition creates spectrum of signals extending to 1GHz and beyond. Suddenly, a Digital Designer finds himself immersed deep into the RF and Microwave enemy territory. What used to be a benign copper trace is now a mysterious transmission line; a previously friendly ground plane is now a battleground of unseen currents; and the entire board is suddenly a combination of self-resonances that are eager to take any fast transient and generate unfriendly vibes. All these intrusions alter the waveform of the originally intended square-wave signal to often-unrecognizable squiggle. The end result is a non-working circuit, or, at the best, a circuit with problems.

This application note is not intended to be a signal integrity tutorial – there are plenty of books and articles on the subject. Here we are concerned only with the ability to see the true waveform of "contaminated" signals. If signal distortions cannot be seen, the problem may not be recognized and subsequently left not corrected. Flying blind usually results in prolonged and helpless troubleshooting effort where the unseen problem could be corrected only serendipitously.

Conventional Method

A tool for observing signal waveform is an oscilloscope with its probe. At low frequencies your regular oscilloscope probe served you well. It showed you the actual shape of the signal and its magnitude. Would it be true at high frequencies?

Did it ever happen to you or to your colleague that connecting a scope probe to a malfunctioning circuit suddenly made it work (until removed)? A scope probe has finite resistance and capacitance that load the measured signal. Better probes have higher resistance and lower capacitance. But even the best of the best are not flawless – they still come into the contact with the measured signal and alter the very signal they are supposed to observe. The typical features of the signal that conventional probes easily miss are overshoots and undershoots, ringing and peaks and valleys that are caused by resonances in the traces.

New Solution

Every electrical signal generates electromagnetic field. This field can be picked up by a sensitive instrument, amplified and displayed on the oscilloscope – all without contact with the circuit and without affecting measured signal in any way.

As non-contact instruments, ScanEM-C probes do not affect the measured circuit and can reveal signal integrity problems that even the most sophisticated conventional probes miss.

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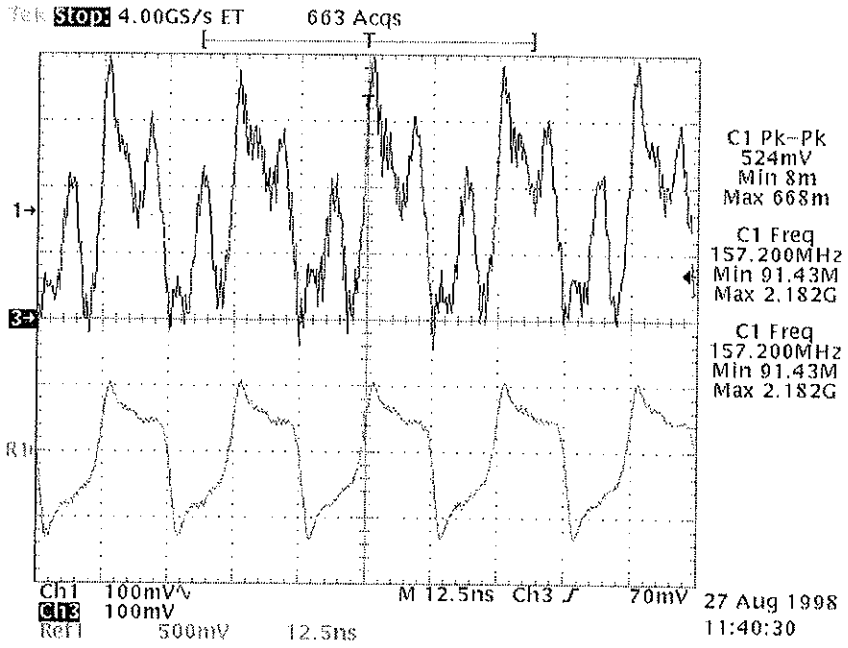
The screen snapshot to the right shows 40MHz signal on a poorly designed board as measured with the 1.5GHz FET probe and the ScanEM-EC probe. Needless to say, the ScanEM-C trace is on the top. (This test used one of the newest 500MHz oscilloscopes.)



As you can see, not only the conventional FET 1.5GHz probe completely missed high frequency ringing, but also it loaded the poorly balanced trace and made certain peaks "disappear."

High frequency ringing caused by trace self-resonance results in excessive electromagnetic emission at frequencies that are not correlated with the clock frequency and therefore hard to locate and correct without proper tools. As evident from the bottom trace, such ringing will simply not be found even with the best of conventional probes.

Large peaks and valleys that are also caused by poor balancing of the traces can easily reach dangerous levels and generate false triggering since magnitudes of these artifacts are comparable with the legitimate logic levels. The evidence of it is in front of you. As seen on the screen snapshot, the oscilloscope misinterpreted ~40MHz signal for a higher-frequency signal (157.2MHz) precisely because such artifacts confused it. Less-sophisticated logic circuit could be even more prone to confusion and malfunction. The FET probe loaded the same signal (bottom trace) to the degree where these peaks and valleys disappeared, but only for the duration of the measurements. After the probe is removed, these artifacts will resume haunting the circuit.

Specifics of ScanEM Applications for Signal Integrity Analysis

Which ScanEM Probe to Use?

ScanEM-EC probe being an electrical field probe shows the voltage on the traces, while magnetic-field ScanEM-HC probe displays AC current in the traces and ground planes.

Use ScanEM-EC probe to monitor voltage where a regular probe would be used.

ScanEM-HC probe used with the oscilloscope allows observation of AC currents up to 1GHz in traces and ground planes without disturbing the circuit in any way.

High-Frequency Current Monitoring

The importance of monitoring high-frequency currents in the circuits was downplayed in the conventional literature for simple reason that there was no instrument available for that. However, high-frequency current artifacts can be just as harmful to the operation of the circuit.

Example: Inductive Coupling Between the Traces

It is very common on high-density boards to see traces run close to each other. This can easily cause inductive coupling at high frequencies – these traces behave simply like windings of an RF transformer with air core. The higher the frequency,

$$p(\theta) = \exp(\alpha\cos\theta)/2\pi I_0(\alpha) \quad (11)$$

By substituting eqns. 1, 3 and 11 into eqn. 4, exact values of the average BER can be evaluated numerically. However, an exact closed-form expression for the average BER does not exist. Therefore, a simple closed-form expression for the approximation of the average BER is derived instead. By employing linear approximation [4], the average BER can be accurately approximated by

$$\bar{P}_e \simeq \frac{1}{2\Gamma(m)}\left(\frac{m}{\Omega}\right)^m \times \int_0^\infty \gamma^{m-1}\mathrm{erfc}\left(\sqrt{\gamma}\frac{I_1(\alpha)}{I_0(\alpha)}\right)\exp\left(-\frac{m}{\Omega}\gamma\right)d\gamma \quad (12)$$

This approximation is virtually indistinguishable from the exact values [4]. By using two additional approximations, namely, $\mathrm{erfc}(z) \simeq \exp(-z^2)/\sqrt{\pi}$ and $I_1(z)/I_0(z) \simeq 1 - 1/2z$ [5], the approximated average BER can be simplified as

$$\bar{P}_e \simeq \frac{1}{2\sqrt{\pi}\,\Gamma(m)}\left(\frac{m}{\Omega}\right)^m \times \int_0^\infty \gamma^{m-1}\exp\left\{-\left[\frac{m}{\Omega}+\left(1-\frac{1}{2\alpha}\right)^2\right]\gamma\right\}d\gamma \quad (13)$$

Further manipulation leads to a simple closed-form expression for the approximated average BER as

$$\bar{P}_e \simeq \frac{\exp(1/K)}{\sqrt{\pi}(2K)^m\Gamma(m)}\left(\frac{m/\Omega}{\sqrt{1+m/\Omega}}\right)^m K_m\left(\sqrt{\frac{1+m/\Omega}{K^2}}\right) \quad (14)$$

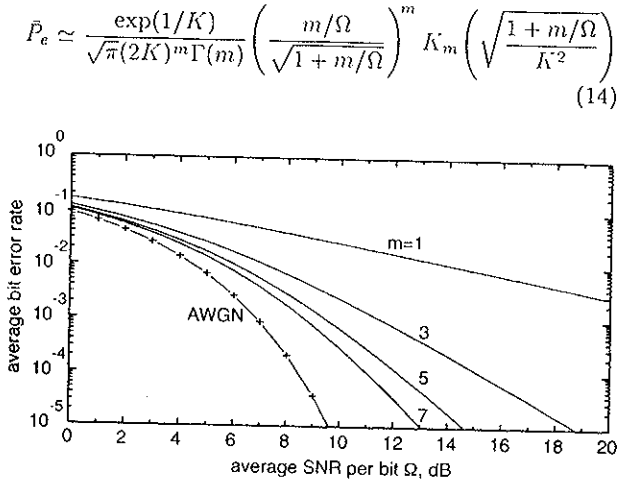


Fig. 1 *Exact values of average BER performance of BPSK in the presence of Nakagami-m fading having m = 1,3,5,7 and Gaussian-distributed phase error with K = 10*

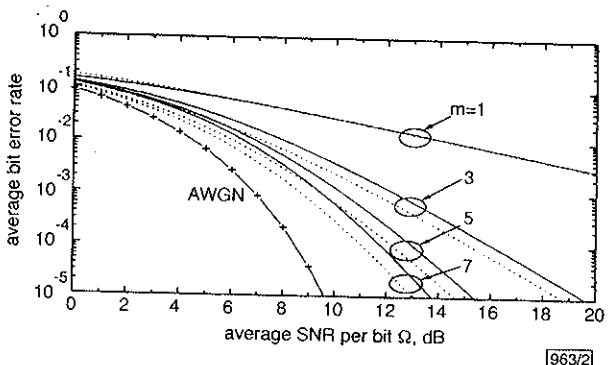


Fig. 2 *Exact and approximated values of average BER performance of BPSK in the presence of Nakagami-m fading having m = 1, 3, 5, 7 and Tikhonov-distributed phase error with K = 10*

——— exact
– – – – approximation

Numerical results: In Fig. 1, exact values of the average BER for BPSK are depicted as a function of the average SNR per bit in the presence of Gaussian-distributed phase noise for several values of the m parameters. The case of nonfading (AWGN) is also shown in Fig. 1 for comparison. Note that K is fixed at 10, i.e. α is 10dB above γ. In Fig. 2, exact and approximated values of the corresponding average BER performance are shown in the presence of Tikhonov-distributed phase noise. Note that the approximation (or lower bound) is very close to the exact values and they virtually merge together when $m = 1$. For both types of phase error PDFs, it is observed that error performance degrades significantly with a decrease in the m parameter, especially when the m parameter is small. Also note that the effects of K and m on the average BER for fixed SNR have not been discussed due to the limited available space.

Conclusion: We have studied the effect of phase noise on the error performance of BPSK systems in the presence of Nakagami-m fading and AWGN. Closed-form expressions which provide a convenient tool for the error performance analysis were derived for the average BER. The analysis assumed phase error with Gaussian or Tikhonov PDFs.

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Measurement of noise source impedance of SMPS using two current probes

K.Y. See and L. Yang

Using two clamp-on current probes, a novel method for measuring the common-mode (CM) and differential-mode (DM) noise source impedance of a switched mode power supply (SMPS) is developed. With proper setup calibration, the method is capable of measuring a wide range of impedance values with good accuracy.

Introduction: Switched-mode power supplies (SMPSs) generate significant levels of conducted electromagnetic interference (EMI). A built-in power line filter within a SMPS is often needed to lower the conducted EMI levels sufficiently in order to meet the regulatory EMI limits. To choose the most effective filter configuration and correct component values for the power line filter, knowledge of the CM and DM noise source impedance of an SMPS is essential [1]. The resonance method has been used to estimate the noise source impedance of an SMPS by terminating the power input of the SMPS with a reactive component that is of opposite type to the noise source reactance [2]. However, the process for choosing the right values of reactive components and for tuning for resonance is rather tedious and cumbersome. The insertion loss method has also been introduced to measure the noise source impedance of an SMPS but certain constraints must be fulfilled,

e.g. the impedance of the inserted component must be much larger or smaller than the noise source impedance [3]. Hence, accuracy deteriorates if these constraints are not met. Based on a two current probes technique, a method for measuring the noise source impedance of an SMPS is proposed in this Letter. Since the two current probes are of the clamp-on type, the measurement setup is simple and does not interrupt the normal operation of the SMPS. With careful calibration of the measurement setup, good accuracy can be achieved for a wide range of impedance values.

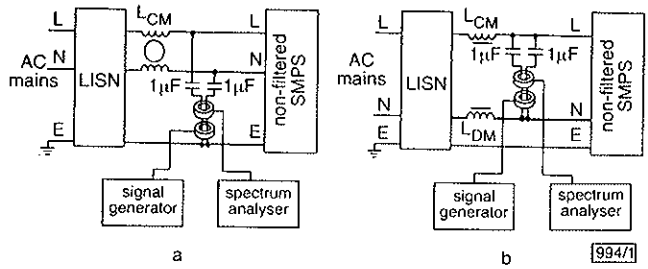

Fig. 1 *Two-current-probe setups for CM and DM noise source impedance measurements*

a CM
b DM

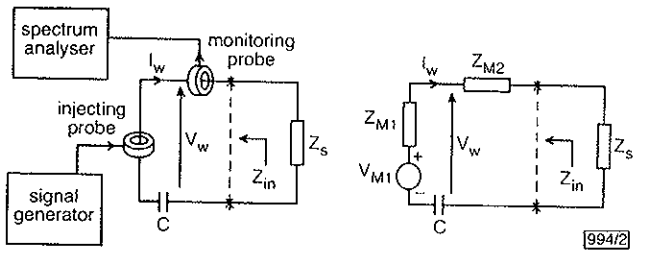

Fig. 2 *Simplified measurement setup and its equivalent circuit*

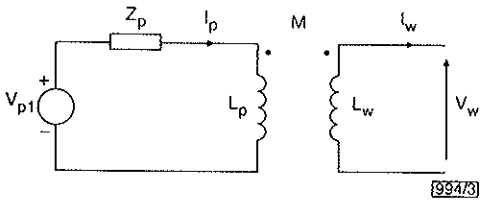

Fig. 3 *Equivalent circuit of injecting current probe*

Measurement setup: Fig. 1 shows the setups for the measurements of the CM and DM noise source impedance of an SMPS. The two current probes and the two 1μF capacitors form a coupling circuit to avoid direct connection to the power mains. To isolate the line impedance stabilisation network (LISN) from the coupling circuit, a CM choke and two DM chokes are inserted between the LISN and the SMPS for the CM and DM measurement setups, respectively. If the chokes provide sufficiently large impedance for the frequencies of interest (100kHz to several megahertz), both the CM and DM setups can be simplified to that shown in Fig. 2. Fig. 3 shows the equivalent circuit of the injecting current probe. V_{p1} is the voltage applied to the terminal of the probe and Z_p is the input impedance of the probe. L_p, L_w and M are the primary self-inductance of the probe, the self-inductance of the wire clamped by the probe, and the mutual inductance between the probe and the wire, respectively. Suppose a current I_w is injected into a wire by the injecting probe, then

$$V_{p1} = (Z_p + j\omega L_p)I_p - j\omega M I_w \quad (1)$$

$$V_w = -j\omega M I_p + j\omega L_w I_w \quad (2)$$

Eliminating I_p from eqns. 1 and 2 gives

$$V_w = V_{M1} - Z_{M1} I_w \quad (3)$$

where

$$Z_{M1} = -\left[j\omega L_w + \frac{(\omega M)^2}{Z_p + j\omega L_p}\right] \text{ and } V_{M1} = \frac{-j\omega M}{Z_p + j\omega L_p} V_{p1}$$

In Fig. 2, V_{M1} is also given as

$$V_{M1} = (Z_{in} + Z_s)I_w \quad (4)$$

Rearranging eqn. 4, the noise source impedance Z_s can be obtained by

$$Z_s = (K_{R1} Z_{T2})\frac{V_{p1}}{V_{p2}} - Z_{in} \quad (5)$$

where $K_{R1} = V_{M1}/V_{p1} = -j\omega M/(Z_p + j\omega L_p)$ and $Z_{T2} = V_{p2}/I_w$, and V_{p1} and V_{p2} are voltages at the terminals of the injecting and monitoring probes, respectively.

By keeping the generator output unchanged, then $(K_{R1}Z_{T2})V_{p1}$ is a constant for a given frequency. If the SMPS is replaced by a known precision standard resistor $R_{std} \gg Z_{in}$, then the constant $(K_{R1}Z_{T2})V_{p1}$ can be obtained through

$$(K_{R1} Z_{T2})V_{p1} \simeq R_{std} V_{p2}\big|_{Z_s = R_{std}} \quad (6)$$

To determine Z_{in}, the wires between the LISN and the SMPS are disconnected and short-circuited to form a closed wire loop. Z_{in} can then be evaluated from

$$Z_{in} = \frac{(K_{R1} Z_{T2})V_{p1}}{V_{p2}\big|_{Z_s=0}} = \frac{R_{std} V_{p2}\big|_{Z_s = R_{std}}}{V_{p2}\big|_{Z_s=0}} \quad (7)$$

Finally, the SMPS is powered up, and the noise source impedance of the SMPS can be determined by

$$Z_s = \frac{(K_{R1} Z_{T2})V_{p1}}{V_{p2}\big|_{Z_s=SMPS}} = \frac{R_{std} V_{p2}\big|_{Z_s = R_{std}}}{V_{p2}\big|_{Z_s=SMPS}} - Z_{in} \quad (8)$$

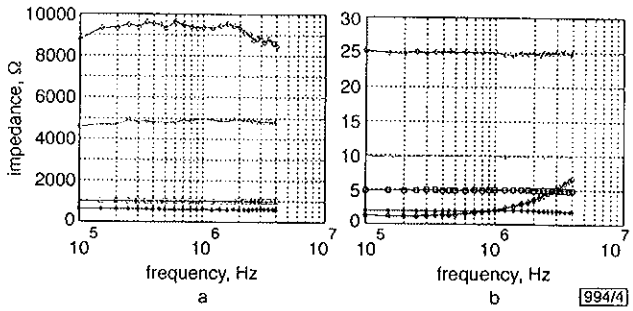

Fig. 4 *Validation of measurement setup*

a Large resistance values
○ 10kΩ □ 1kΩ
◇ 5kΩ ✳ 600Ω
b Small resistance values
○ 25.5Ω □ 5Ω
+ 10Ω ✳ 2Ω
◇ Z_{in}

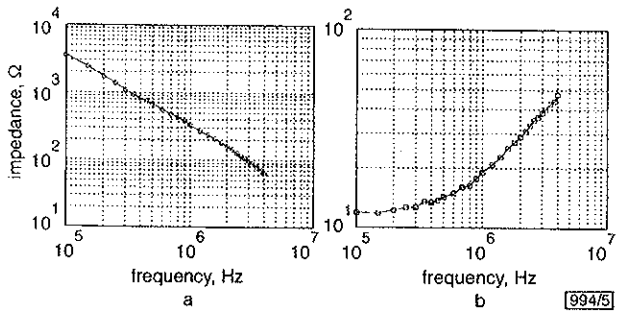

Fig. 5 *Noise source impedance of SMPS*

a CM noise source impedance
b DM noise source impedance

Experimental results: In the experiment that follows, Tektronic CT-1 and CT-2 current probes were used as the injecting and monitoring current probes, respectively. Both current probes were broadband types with bandwidths of ~700MHz. The first step was to measure Z_{in} according to eqn. 7. Z_{in} was found to have a resistance of 1.2Ω in series with an inductance of 0.27μH. To obtain $(K_{R1}Z_{T2})V_{p1}$ for the measurement setup as a calibrated reference, the SMPS was replaced by a 100Ω standard resistor (R_{std}) and the

constant $(K_{R1}Z_{T2})V_{p1}$ was evaluated from eqn. 6. For validation purposes, other resistors of known values were connected and measured. Good measurement accuracy for both large and small resistor values was demonstrated, as shown in Figs. 4*a* and *b*. Fig. 4*a* reveals that even Z_{in} is very small; its effect cannot be ignored when the noise source impedance to be measured becomes small. Finally, an SMPS, model Astec RBS22, was connected and powered up. The CM and DM noise source impedance was measured in accordance with eqn. 8, and the impedance curves plotted in Figs. 5*a* and *b*, respectively. The measured CM noise source impedance curve indicates that its impedance is purely capacitive, with a capacitance of 500pF. The DM noise source impedance curve suggests that the impedance can be represented by a resistance of 10.5Ω in series with an inductance of 1.5μH.

Conclusion: The two current probes technique has been experimentally verified to be an efficient and accurate method for measuring the noise source impedance of an SMPS. With the knowledge of noise source impedance, the most effective filter configuration and optimal component values can be chosen to design a power line filter. This will avoid over-design of a power line filter and hence reduce its cost.

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Low threshold current density operation of GaInNAs quantum well lasers grown by metalorganic chemical vapour deposition

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A metal organic chemical vapour deposition grown GaInNAs quantum well laser emitting at 1.25μm is reported. The lowest threshold current density obtained by 50μm wide stripe lasers was 340A/cm² for a cavity length of 1420μm, which is almost comparable to the lowest value reported for GaInNAs lasers grown by molecular beam epitaxy. The threshold current density per well was 170A/cm², which is the lowest threshold value reported to date.

Introduction: GaInNAs has been widely studied since its proposal in 1996 [1] and is particularly used as an active layer in GaAs based long-wavelength vertical-cavity surface-emitting lasers (VCSELs) [2]. Many methods for growing GaInNAs lasers have been studied, including gas-source molecular beam epitaxy (GS-MBE) [3], solid source molecular beam epitaxy (MBE) [4, 5], chemical beam epitaxy (CBE) [6], and metal organic chemical vapour deposition (MOCVD) [7, 8]. Recently, the threshold current densities of GaInNAs quantum well lasers have been significantly reduced by MBE growth using a radical cell [5, 9]. Although several research groups have reported on GaInNAs lasers grown by MOCVD, the lowest threshold current density is still two times larger than that of MBE-grown lasers. Reducing the threshold current density of MOCVD-grown GaInNAs lasers is desirable, since it is beneficial to use MOCVD for industrial production. In this Letter, we report the lowest threshold current density operation of MOCVD-grown long-wavelength GaInNAs QW lasers. A threshold current density lower than the recently reported record for MBE-grown GaInNAs QW lasers has been obtained.

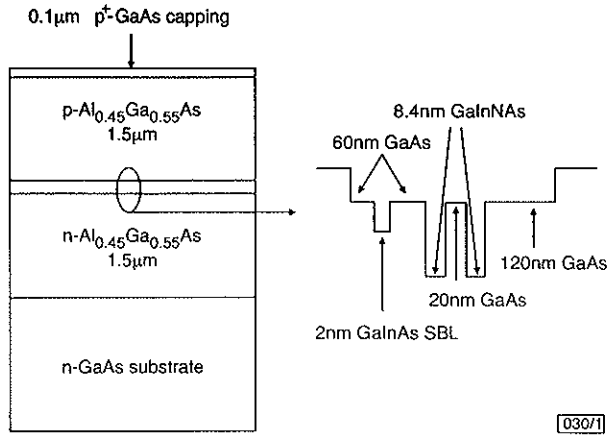

Fig. 1 *Schematic diagram of laser wafer*

Growth and device fabrication: The laser device structure wa grown by low pressure MOCVD on an Si-doped (100) GaAs sub strate. Triethylgallium (TEGa), trimethyl indium (TMIn) and tri methylaluminum (TMAl) were used as the group III sourc materials and dimethylhydrazine (DMHy) and tertiarybutylarsin (TBAs), which is a safer As source to AsH_3, were used as th group V source materials [10]. Silane (SiH_4) and dimethylzin (DMZn) were used as the *n*- and *p*-type doping materials. A sche matic diagram of the laser wafer is shown in Fig. 1. Since th photoluminescence (PL) intensity from GaInNAs QWs continu ously grown on an *n*-AlGaAs cladding layer in the same MOCVI reactor showed significant degradation, the active layer and clad ding layers were grown in different MOCVD reactors. At th interfaces located in the GaAs separate confinement heterostruc ture (SCH) layer, the wafer was taken out into the air to chang the reactor. The detail of this MOCVD degradation phenomeno will be discussed elsewhere. The active layer of the laser consists c 84Å thick double $G_{0.68}In_{0.32}N_{0.007}As_{0.993}$ QWs and 200Å thic GaAs barrier layers. A strained buffer layer was inserted to main tain good crystal quality of the strained GaInNAs QWs [11]. Th conditions under which the GaInNAs QWs were grown were carc fully optimised, and the growth details will be published elsewher The 1.5 μm thick *n*- and *p*-type $Al_{0.45}Ga_{0.55}As$ cladding layers wer doped with 1×10^{18} and 5×10^{17} cm^{-1}, respectively. A 0.1μm thic *p*-GaAs layer of ~3×10^{19} cm^{-1} was used as the capping. Th grown wafer was processed for use in two types of broad contac laser, an oxide-mask stripe laser with a width of 20μm and a ridg stripe laser with a stripe width of 50μm.

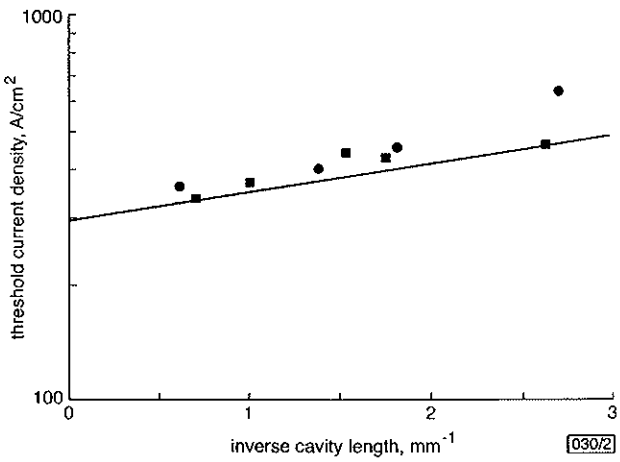

Fig. 2 *Threshold current density dependence of inverse cavity length a room temperature*

● oxide-mask lasers with 20μm stripe width
■ ridge stripe lasers with 50μm stripe width
λ = 1.25μm, CL/CL

Result: The devices were measured under pulsed operation with pulse width of 3μs and a repetition rate of 1kHz at room tempe ature. The emission wavelength of the cavity length of 720μm wa

CONTROLLING RADIATED EMI FROM DIGITAL CIRCUIT THROUGH PROPER PCB LAYOUT

by K. Y. See, T. H. Ooi & Y. Zhao

ABSTRACT

Meeting EMI (electromagnetic interference) regulations with minimal costs is of growing concern to manufacturers worldwide. High-speed digital circuits, if not properly routed on PCBs, can radiate significant levels of EMI. This paper demonstrates the importance of good PCB layout practices in controlling radiated EMI.

INTRODUCTION

With the current trend of ever increasing clock speeds, digital circuits become unintentional radio frequency transmitters. The spectral contents of these high-speed digital signals cover a very wide frequency range, from several MHz to well above 1 GHz. Hence, if the levels of radiated fields from high-speed digital circuits are not properly regulated, they can be potential interference sources to other intentional communications users. To ensure electromagnetic compatibility (EMC), more and more countries are imposing mandatory EMI limits to electronic products [1-3]. Hence, digital design is no longer just to get the circuit working but also to meet the stringent EMI limits.

Unfortunately, most design engineers leave the EMI issues to the later phase of product development. If EMI control is not taken into consideration in the early phase of product development, such as proper PCB layout, the solutions to lower EMI at the later phase, such as adding shields and filters, can be very expensive. Hence, proper layout of a digital circuit on a PCB plays an important role for cost-effective EMI compliance. The most important consideration when making a PCB layout is to minimize power-ground and signal-ground loops. Large circuit loops can cause direct differential-mode radiation. These loops also give rise to different ground potentials across ground conductors, leading to common-mode radiation.

To demonstrate the impact of PCB layout on radiated EMI, a digital circuit uses a 10 MHz clock oscillator to drive several counters, as shown in Figure 1, is used for the case study. Two different layouts with the same digital circuit are routed on single-layer double-sided PCBs of identical size. Figures 2 and 3 show the PCB layouts with and without EMI consideration, respectively. For PCB layout #1, the power and ground conductors are far apart, forming large loops for switching currents when the IC modules switch states. Also, the signal return paths between IC modules are forced to go through large loops to get back to the driving gates. PCB layout #2 dedicates one complete side of the PCB as ground plane. The ground plane serves as an image plane for all power and signal returns. This arrangement allows the power and the signal currents to find their adjacent return paths with the smallest possible loop areas.

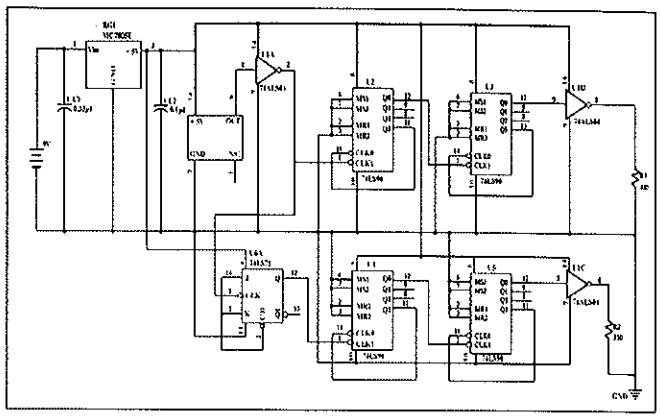

Figure 1: Digital Circuit for Case Study

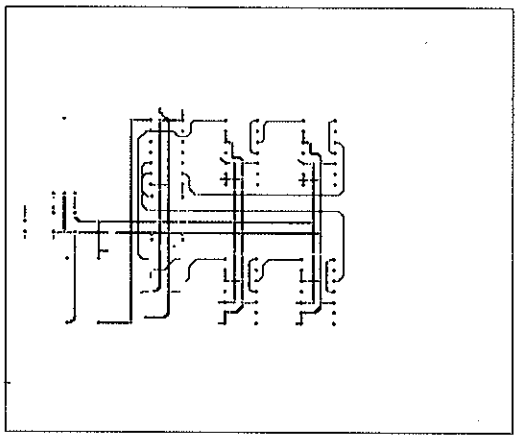

Figure 2: PCB Layout #1 without EMI Consideration

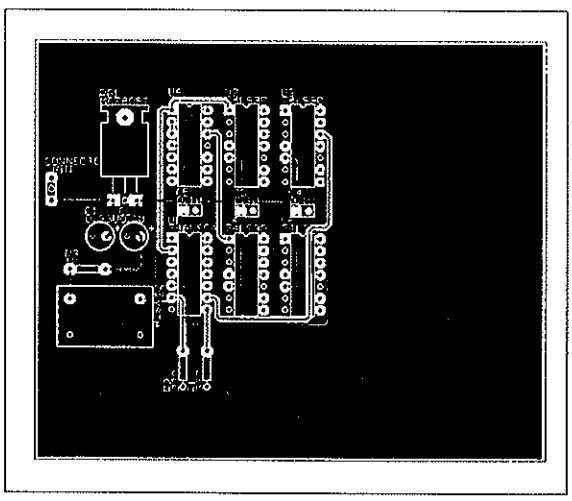

Figure 3: PCB Layout #2 with EMI Consideration

MEASUREMENT RESULTS

The two layouts are fabricated on two PCBs. A Giga-hertz Transverse Electromagnetic (GTEM) Cell, as shown in Figure 4, is used to measure radiated emissions from the two PCBs. The measured levels are compared with the CISPR 22 class B radiated EMI limits [4], in the frequency range of 30 to 1000 MHz. The measured results for layout #1 and layout #2 are given in Figures 5 and 6, respectively.

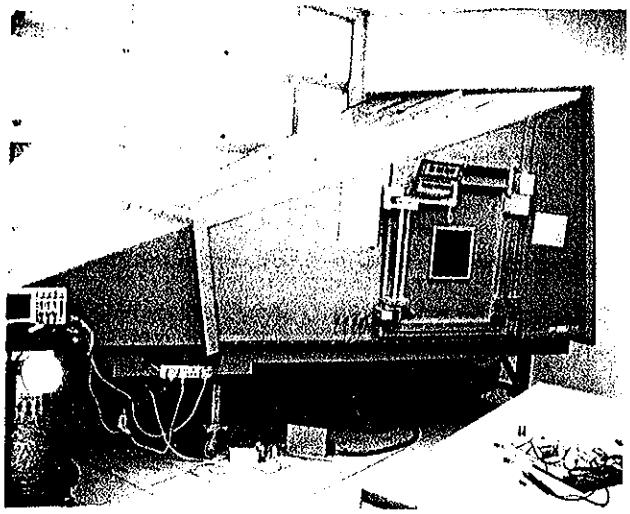

Figure 4: GTEM Cell for Radiated EMI Measurement

Figure 5 shows radiated emissions from layout #1. The emission frequencies are the harmonics of the 10 MHz clock oscillator. It shows clearly that even a very simple digital circuit with a 10 MHz clock can radiate significant level of EMI. By comparing the emissions with the CISPR 22 class B limits, it is obvious that radiated emissions around 300 to 400 MHz have exceeded the required limit.

Figure 6 shows that the extra effort put in for layout #2 is rewarded by significant reduction of radiated emissions. In general, about 20 to 30 dB reduction of radiated emissions is observed across the 30 to 1000 MHz frequency range.

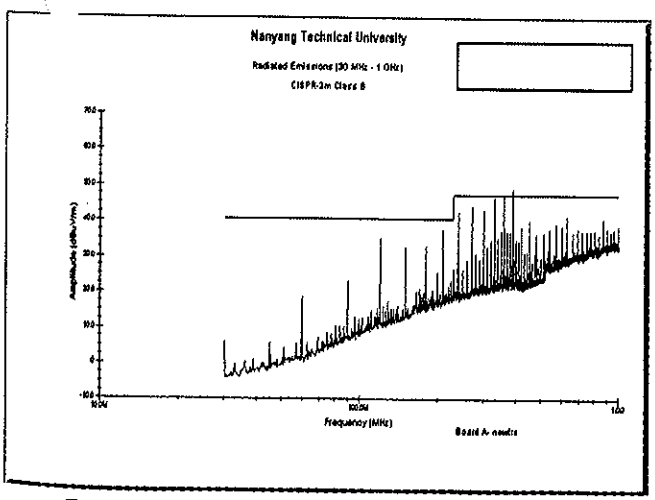

Figure 5: Radiated Emission from PCB Layout # 1

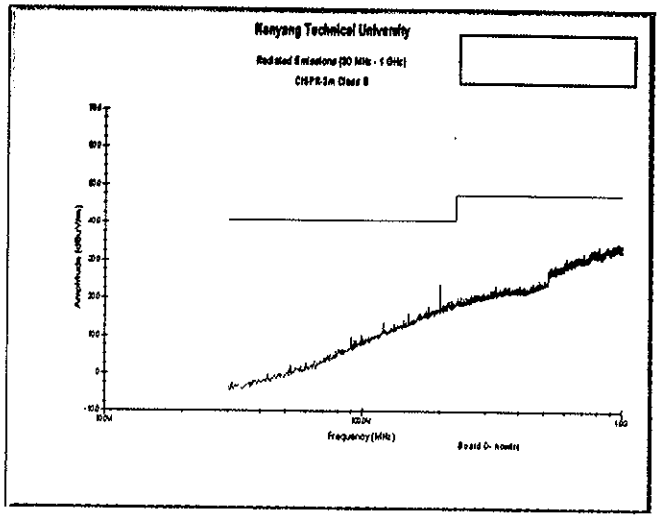

Figure 6: Radiated Emission from PCB Layout # 2

CONCLUSION

In this paper, a simple digital circuit with a 10 MHz clock is used as an example to illustrate the importance of good PCB layout practices for EMI compliance purposes. The layout strategy addressed in this paper is in fact very simple, that is never to take for granted that the signal return path would take care of itself. Any uncontrolled power-ground and signal-ground loops that carry high-speed switching currents with high spectral contents can easily cause a product to fail the regulatory EMI limits. Adopting good PCB layout practices not only cut-down the time for EMI compliance, but also eliminate the needs for last minute costly EMI fixes, such as adding shields, ferrites and filters to the product.

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like a conventional spiral Rogowski coil when protected by heat-shrink and with a BNC terminal attached. The normal sensitivity tests were carried out with a two-turn braid Rogowski coil for which the expected sensitivity was $2\mu_0 n A = 128.5$nH. The measured sensitivity was 127.7nH. Noting that the machine manufacture, for the prototype, gave an open braid with possibly half the area of the core tube visible, it is expected that these figures could be substantially improved, even without using finer wires.

The measurement setup in Fig. 3 shows the braided Rogowski coil positioned for an edge test [3]. (The coil is rotated through 90° to measure the residual signal.) The 'teardrop' shape is preferred to a buff-joint because it tends to present end-turns parallel to the field of the measured current. This test circuit has a 10-turn primary coil with sinusoidal $I(t)$ up to 1.5A peak at typically 2.5kHz. The coil limb is centred in an insulating tube, 25mm diameter, to give comparability with USA practice [3]. The edge-test output, taken through a ×100 preamplifier to a DVM, is expressed as a percentage of the normal output $e(t)$ when the same Rogowski coil measures the same $I(t)$ by enclosure. Thus the results for three coils detailed in Table 1 are directly comparable, and describe just the relative performance of the different geometries.

The results in Table 1 show, first, the clear superiority of the bootlace Rogowski coil over the rigid toroidal Rogowski coil. It was made to have similar overall dimensions and similar sensitivity in normal use. Noting that the bootlace coil was hand-wound, relying on wire-contact for uniform spacing, the advantage could probably be increased were the solid former to be indexed with helical grooves, at some greater cost. The braid coil is significantly better than the bootlace coil. As the first of a kind it could with practice be made with turns much closer together, which would increase the normal sensitivity and improve the uniformity; these changes would both be of benefit to the edge test percentage.

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Network for conducted EMI diagnosis

K.Y. See

A novel network is developed for conducted electromagnetic interference (EMI) diagnosis. Using the network together with the line impedance stabilisation network (LISN), common mode (CM) and differential mode (DM) conducted EMI are discriminated from each other. This capability allows conducted EMI diagnosis to be carried out efficiently.

Introduction: The LISN is a standard network for measuring the conducted EMI generated by an electronic product. It prevents external conducted noise at the power mains from contaminating the measurement. It also maintains a well-defined live-to-ground and neutral-to-ground impedance (usually 50Ω) for repeatability of the measurement. The interference currents generated by the equipment under test (EUT) consist of two conduction modes. Differential mode (DM) currents flow out of the live wire and return via the neutral wire. Common mode (CM) currents take the live and neutral wires as one outgoing conductor and return via the ground wire. Hence, the DM currents in the live and neutral wires are equal in magnitude and opposite in phase, while the CM currents are equal in both magnitude and phase. The conducted emissions measured by the LISN can be expressed as follows:

$$V_{L-G}(\omega) = 50[I_{CM}(\omega) + I_{DM}(\omega)] = V_{CM}(\omega) + V_{DM}(\omega) \quad (1)$$

$$V_{N-G}(\omega) = 50[I_{CM}(\omega) - I_{DM}(\omega)] = V_{CM}(\omega) - V_{DM}(\omega) \quad (2)$$

$V_{L-G}(\omega)$ and $V_{N-G}(\omega)$ are the conducted emissions measured by the LISN at the live-to-ground and neutral-to-ground terminals, respectively. Eqns. 1 and 2 show that the LISN alone can only measure either the sum or difference of $V_{CM}(\omega)$ and $V_{DM}(\omega)$. However, to provide additional clues for conducted EMI diagnosis, $V_{CM}(\omega)$ and $V_{DM}(\omega)$ must be separated from each other and measured independently. If $V_{CM}(\omega)$ and $V_{DM}(\omega)$ are known, then appropriate CM or DM filter components can be added to the EUT systematically, without the usual trial-and-error process. Some work has been carried out in the area of the discrimination of CM and DM conducted emissions. The differential mode rejection network can only reject DM emissions and measure CM emissions [1]. The mode-select rejection network requires a mechanical switch to select either the CM or DM emissions [2]. The switch introduces network imbalance and affects the high frequency CM/DM discrimination capability. In this Letter we present a novel discrimination network that provides CM/DM rejection without the use of a switch.

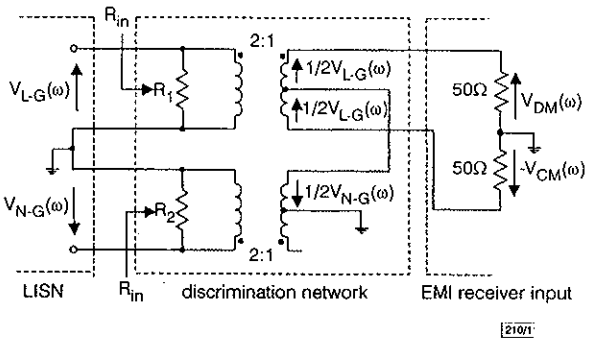

Fig. 1 *CM/DM discrimination network*

Design of network: Rearranging eqns. 1 and 2, $V_{CM}(\omega)$ and $V_{DM}(\omega)$ can be expressed as follows:

$$V_{CM}(\omega) = \frac{1}{2}[V_{L-G}(\omega) + V_{N-G}(\omega)] \quad (3)$$

$$V_{DM}(\omega) = \frac{1}{2}[V_{L-G}(\omega) - V_{N-G}(\omega)] \quad (4)$$

Two wideband RF transformers (Coilcraft P/N: WB2010-PC) with centre-tapped secondaries are connected as shown in Fig. 1 to achieve the adding and subtracting functions of $V_{L-G}(\omega)$ and $V_{N-G}(\omega)$ described in eqns. 3 and 4, respectively. The CM and the DM conducted emissions are now separated from each other and are measured directly with an EMI receiver. Two resistors R_1 and R_2 are added across the input of the network in order to terminate the LISN with 50Ω. For R_{in} to be 50Ω, the values of R_1 and R_2 are found to be 100Ω each [3].

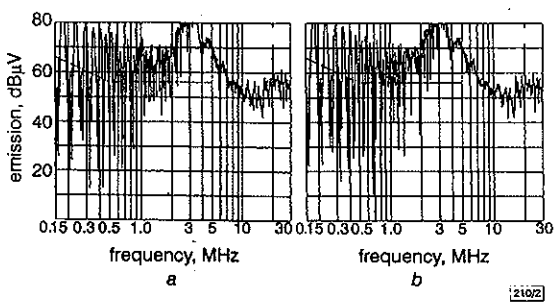

Fig. 2 *Live and neutral emissions without filter*
a Live
b Neutral

Experimental results: Based on the design in Fig. 1, a network was constructed. A functional test on the network was carried out to check its CM/DM discrimination capability. In the frequency range 10kHz–50MHz, the lowest CM and DM rejection ratios were found to be 38 and 33dB, respectively. Hence, the network is able to isolate the CM or DM signal sufficiently for EMI diagnosis purposes. To demonstrate its practical application, a 24W switched-mode power supply (ASTEC model: RBS22) with 100% loading was used as an EUT. With all the power line EMI filter components in the EUT removed, the conducted emissions of the live and neutral wires measured by the LISN are given in Fig. 2. It is obvious that the EUT failed to comply with EN 55022 class B limits [4] but the measurement does provide some useful clues for EMI diagnosis purposes. Connecting the discrimination network to the LISN, the CM and DM conducted emissions were measured separately.

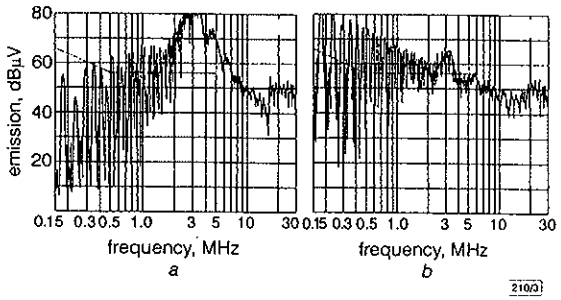

Fig. 3 *CM and DM emissions without filter*

a CM
b DM

Fig. 3 shows clearly that the CM emissions dominate in the 1.5 to 8MHz range, whereas the DM emissions dominate at the lower frequency end of 150kHz to 1MHz. Since the dominant conduction mode at a specific frequency range is identified, appropriate CM or DM EMI filter components will be added accordingly. As a start, a 5mH CM choke was inserted into the power line input of the EUT, and the CM and DM emissions were measured again.

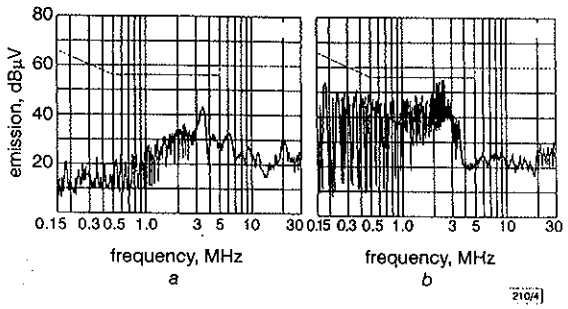

Fig. 4 *CM and DM emissions with CM choke*

a CM
b DM

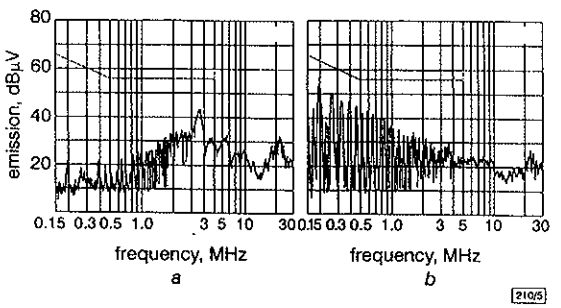

Fig. 5 *CM and DM emissions with CM choke and DM capacitor*

a CM
b DM

Fig. 4 shows that the CM emissions are suppressed significantly below the limits. The leakage inductance of the CM choke also serves as a DM inductance, which attenuates the DM emissions but not as much as those of the CM emissions. To provide comfortable EMI margins for the DM emissions at ~2MHz, a 0.1μF capacitor was added across the live and neutral lines of the EUT. Fig. 5 shows that the capacitor has no impact on the CM emissions but it reduces the DM emissions further. Both the CM and DM emissions are now well below the limits. As a final check for EMI compliance, the discrimination network was removed from the LISN, and the conducted emissions for the live and neutral line were measured again. Fig. 6 shows that the EUT has now complied with the limits.

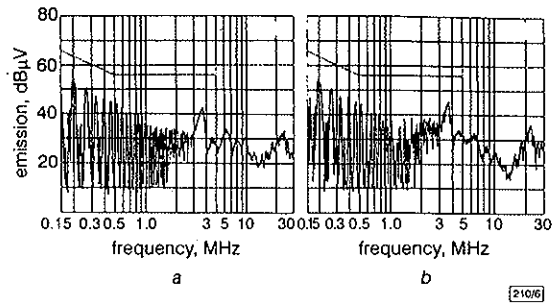

Fig. 6 *Live and neutral emissions with CM choke and DM capacitor*

a Live
b Neutral

Conclusion: A novel CM/DM discrimination network has been developed and has proven to be a useful tool for conducted EMI diagnosis.

Acknowledgment: The author would like to thank his student, K.W. Ow-Yeong, for the construction of the network.

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Worst-month rain statistics for radiowave propagation study in Malaysia

J. Chebil and T. Abd. Rahman

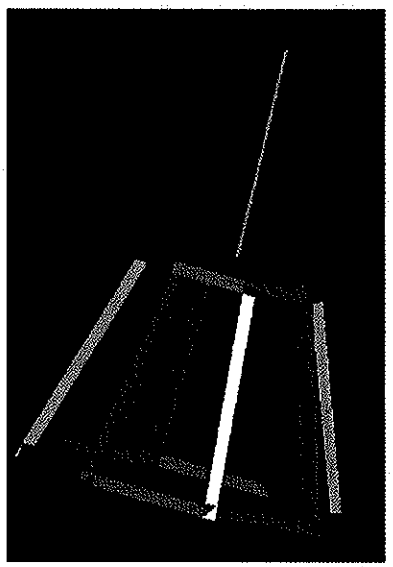
A study of the worst-month rainfall rate statistics for the Malaysian environment is presented. Rain rate data with 1 min integration time were collected in the Universiti Teknologi Malaysia and the Universiti Sains Malaysia. The relationship between the worst month and the yearly probabilities is presented and the ITU-R model verified. For better precision, new values are proposed for the parameters Q_1 and β in Malaysia.

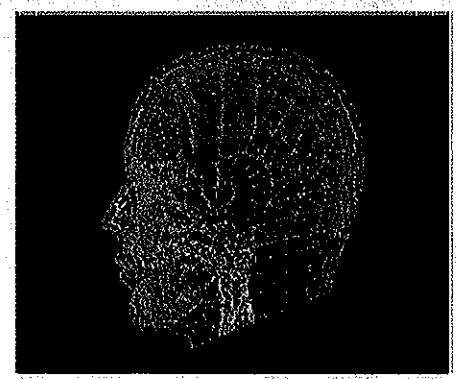
Introduction: Rainfall is a serious cause of attenuation for radiowave propagation at frequency bands above 10GHz. It is important to accurately predict the fading outage due to rain attenuation. Although the prediction method recommended by the ITU-R is suitable for temperate regions, it is not as suitable for tropical and equatorial regions. This is due mainly to the lack of rainfall and rain attenuation data in these regions. Rain attenua-

ELECTROMAGNETIC COMPATIBILITY

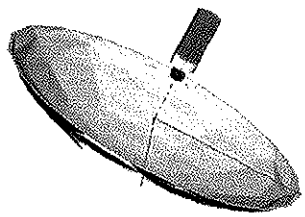
Projects

- EMI analysis of a USB floppy drive
- Design, simulation and development of a reverberation chamber
- Signal integrity and radiation analysis of a discrete I/O PCB
- Simulation of a printer's multi-layer circuit board
- Analysis of antenna coupling in the presence of mast
- Antenna radiation computation and analysis
- Electromagnetic field simulation in a vehicle
- Magnetic shielding and mitigation





Simulation of radiation in a human head



Design and simulation of an antenna



Analysis of radiation field and coupling of vehicular antenna

Research & Industry Partners

- Advanced Micro Devices (S) Pte Ltd
- CET Technology Pte Ltd
- Defence Science & Technology Agency
- Delphi Automotive Systems Singapore Pte Ltd
- DSO National Laboratories
- Hewlett-Packard Singapore (Pte) Ltd
- Mentor Graphics Asia Ltd
- Ministry of Defence
- SingaporeTechnologies Electronics Ltd
- SingaporeTechnologies Aerospace Ltd
- University of Illinois at Urbana-Champaign (US)

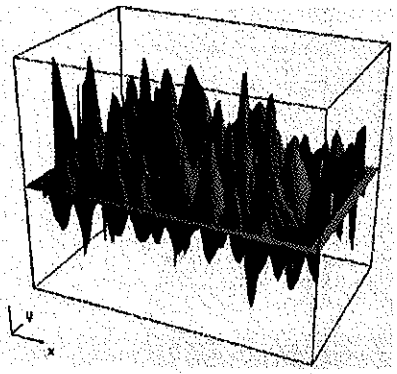
iHPC

Institute of
High Performance Computing

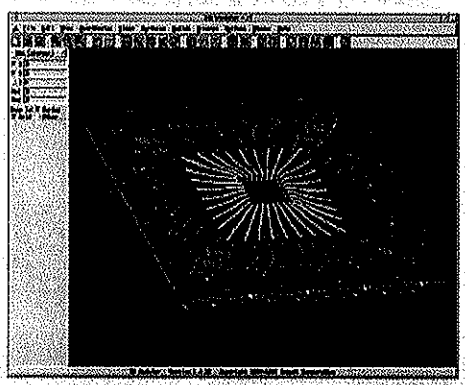
ELECTROMAGNETIC COMPATIBILITY

Research Strengths

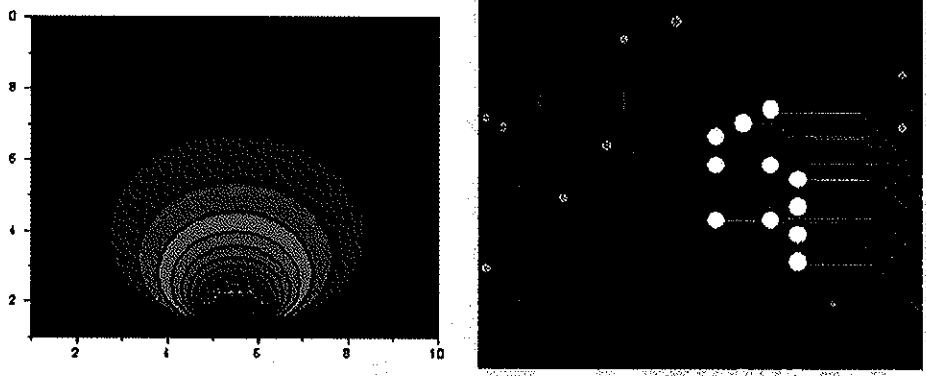
- Signal integrity and EMC analysis and simulation
- Electromagnetic interference (EMI) in high-speed PCB and IC designs
- High-speed electronic design
- Optimal design of reverberation chamber
- Development of EDA tools
- Bio-electromagnetics
- Computational electromagnetics
- Radio frequency and antenna analysis and design
- Radar cross-section simulation



E-field distribution in a reverberation chamber using the FDTD simulation method



Numerical modelling of EMI in high-speed IC packaging



Field distribution around the power and ground planes in a multi-layer PCB

Application Areas

- IC and circuit modelling and simulation
- Biomedical device development
- Defence engineering EMC/EMI management
- Aerospace electronic system EMC management
- EMC design and testing

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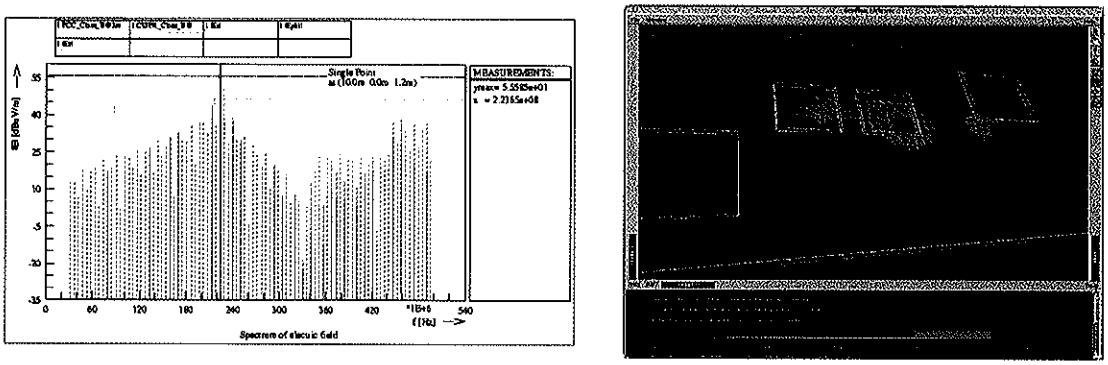
EMI Research Consortium for High-Speed Electronics

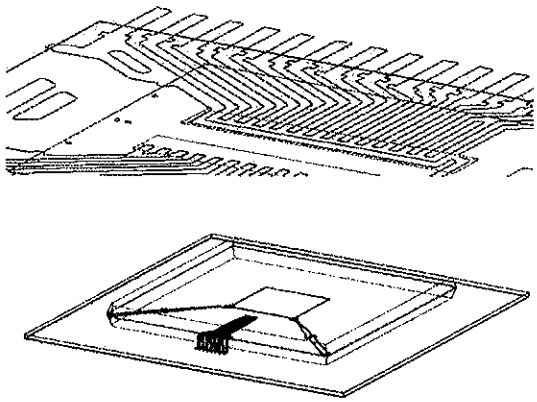
The continuous increase in operating speed of electronic systems is driving the semiconductor industry to develop electronic components, especially microprocessors, with higher clock rates and shorter rise and fall time. This calls for high-speed technology. However, an increase in the operating speed of such systems will lead to an increase in electromagnetic interference (EMI), which affects the performance of the system. Therefore, intensive research in high-speed electronics, and electromagnetic compatibility (EMC) and EMI is essential to maximise speed, minimise interference and improve the overall performance of such systems.



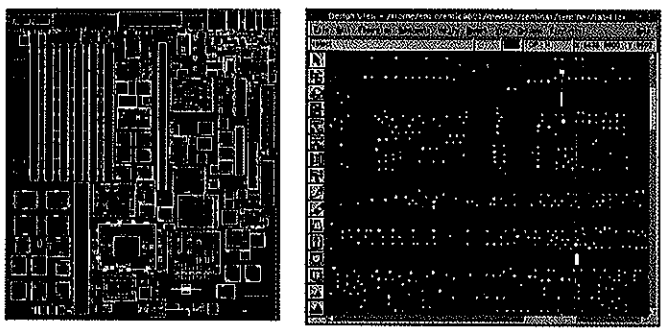
PCB emission and field scan

One of the objectives of the EMI Research Consortium for High-Speed Electronics (ECHE), initiated by the Institute of High Performance Computing, is to bring together a centralised pool of experts and resources in developing high-speed printed circuit board (PCB) design, high-speed packaging, EMI modelling and EMC designs. In addition, the consortium will also provide training and consultation to its members.

Presently, increasing time-to-market pressures require more efficient ways to deliver high-speed electronic products. Demands for high-speed designs are dramatically increasing. The consortium will work to deliver high-speed design technologies and transform electrical rules to practical designs with commercial applicability. This will benefit consortium members and enable them to meet the design objectives for today and tomorrow.



IC packaging and parameter extraction



Signal integrity: crosstalk screening

Main Activities of the Consortium

Research
- high-speed PCB design
- high-speed IC modelling
- EMI expert system

Training
- short courses on high-speed electronics and EMC/EMI
- Workshops on specific topics in related areas
- industrial attachment
- seminars

Project Consultation
- signal integrity analysis
- conducted and radiated emission
- IC modelling
- RF-related topics
- EMC control
- Other EMC/EMI issues

For more information on the consortium, please contact Dr. Li Er Ping, EMC Division Manager at telephone number 7709900 or email him at eplee@ihpc.nus.edu.sg.

For more information about IHPC and to learn about the core competencies of the EMC division, please visit the IHPC website at http://www.ihpc.nus.edu.sg.

89C Science Park Drive, #02-11/12 The Rutherford Singapore 118261

Institute of High Performance Computing

Credence Technologies ScanEM Probes



EDN 100 Hottest products of 1994

EDN 100 Hottest products of 1995

Shorten your development schedule and save money on product re-design by using proper EMC tools from the beginning of the project.

ScanEM$^{\diamond}$ probes are the most versatile, affordable, and handy instruments for detecting, locating and measuring of electromagnetic emission. Professionals in small and large companies all over the world use ScanEM probes. In the U.S., FCC is using ScanEM-Q probes to enforce compliance with the FCC rules in the field.

ScanEM probes will help you to reliably predict EM behavior of your product and to locate emission sources in a matter of seconds. They detect presence of an electromagnetic field and provide audio and visual indication of its relative strength. ScanEM probes can pinpoint exact sources of emission down to a single trace or component.

Connect ScanEM-C probes to a spectrum analyzer and get the best-performing near-field probes in the industry. ScanEM-C probes have a low-noise amplifier built-in. They provide strong broadband output signal that allows you to see what you have been missing using passive probes.

As ultra-wide bandwidth non-contact voltage and current probes for an oscilloscope, ScanEM-C probes will reveal previously invisible transients. As an EM field probe for a multimeter, ScanEM-C probes provide DC voltage that is a function of the field strength.

Ordering Information

Description	Model
ScanEM-C Probe Kit (includes E- and H-Field Probes with RF and DC output), batteries, 6' RF cable, heavy-duty plastic storage enclosure and User's Guide	**CTK015**

To Order: **CET Technologies Pte Ltd**
EMC Centre
24 Ang Mo Kio Street 65
Singapore 569061
Tel.: 65-483 6092
Fax : 65-484 8842
http://www.cet.st.com.sg

An Overview of Electromagnetic Compatibility



A/Professor See Kye Yak
School of Electrical and Electronic Engineering
Nanyang Technological University

History of RFI/EMI

- 1901: first wireless transmission by Marconi
- 1920s: RFI to radio receivers due to other transmitters
- 1930s: RFI to radio receivers due to motors, electric railroad and electric signs
- 1940s: more RFI problems reported due to heavy usage of radio equipment and electronics in military services
- 1950s: invention of BJT
- 1960s: development of ICs
- 1970s: development of microprocessor chips
- 1980s: widespread use of digital control
- 1990s: explosive growth of wireless communications

Degrees of EMI Problems

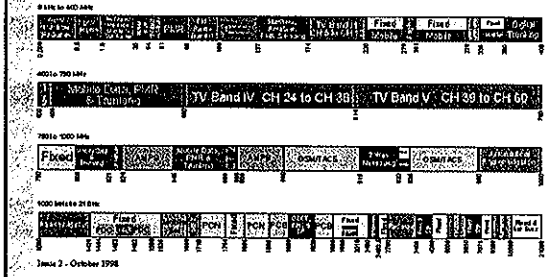
- Nuisance

  The EMI event usually lasts for a short duration and causes no damage
- Catastrophic

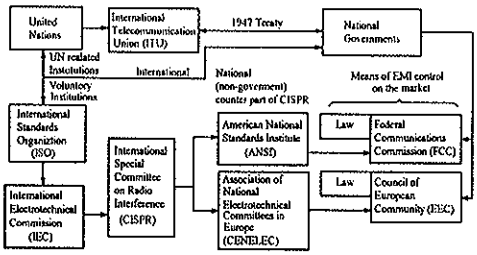
  The EMI event leads to serious consequences such as loss of life or extensive damage
- Intermediate

  Most EMI events are fall between nuisance and catastrophic

Singapore Spectrum Allocation Chart



National Lawmaking Process



Electrical Dimensions

Electrical dimensions are measured in wavelength:

$$\lambda = \frac{v}{f} \quad \text{m}$$

v is the velocity of propagation of EM wave in free space (3×10^8 m/s)

f is the frequency of the signal concerned

Wavelengths at Different Frequency (in Air)

Frequency	Wavelength
50 Hz	6,000 km
3 kHz	100 km
30 kHz	10 km
300 kHz	1 km
3 MHz	100 m
30 MHz	10 m
300 MHz	1 m
3 GHz	10 cm
30 GHz	1 cm

EMI Analysis Methods/Tools

- Electrically small circuits
  - Physical dimension $< 0.1\ \lambda$
  - KVL, KCL and lumped circuit modeling can be used for analysis
- Electrically large circuits
  - Physical dimension $> 0.1\ \lambda$
  - Full-wave approach is the only method for analysis

Common EMI Units in Decibel

- Conducted EMI units

$$dB\mu V \equiv 20\log\left(\frac{Volts}{1\mu V}\right)$$

$$dB\mu A \equiv 20\log\left(\frac{Amps}{1\mu A}\right)$$

- Radiated EMI units

$$dB\mu V/m \equiv 20\log\left(\frac{V/m}{1\mu V/m}\right)$$

$$dB\mu A/m \equiv 20\log\left(\frac{A/m}{1\mu A/m}\right)$$

Linear to Decibel Conversion

- Example 1: Express 23 mV in unit of $dB\mu V$

$$23\ mV = 23\times10^{3}\ \mu V$$

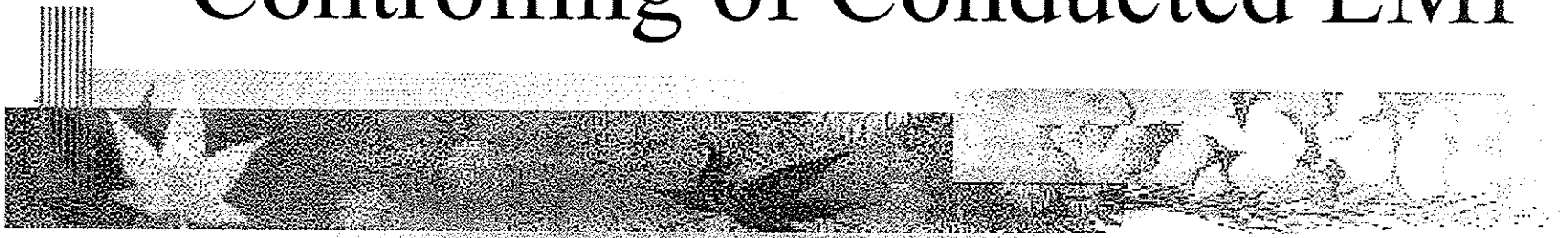
$$20\log\frac{23\times10^{3}\ \mu V}{\cdots} = 87.2\ dB\mu V$$

- Example 2: Express 200 V/m in unit of $dB\mu V/m$

$$200\ V/m = 200\times10^{6}\ \mu V/m$$

$$20\log\frac{200\times10^{6}\ \mu V/m}{\cdots} = 166\ dB\mu V/m$$

Controlling of Conducted EMI

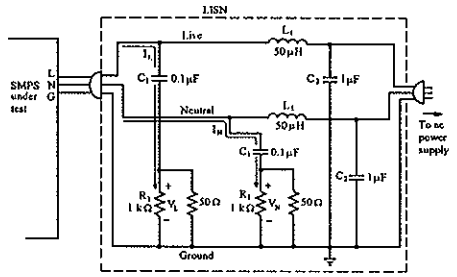


A/Professor See Kye Yak
School of Electrical and Electronic Engineering
Nanyang Technological University

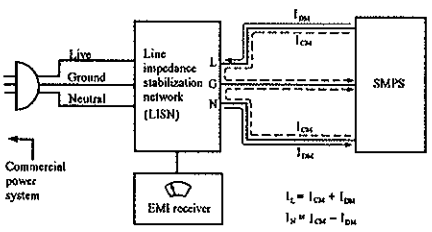
Major Sources of Conducted EMI

- High efficiency and small size → widespread use of high frequency switched mode power supply (SMPS) in electronic products
- Ever increasing switching speed of the power conversion process generates significant conducted EMI
- Proper control to suppress conducted EMI is needed to minimize interference to other users who share the same ac power mains

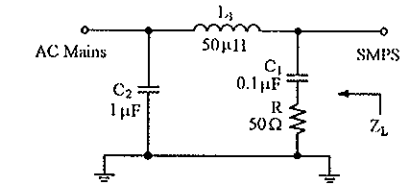
Line Impedance Stabilization Network



Conduction Modes of Interference Currents

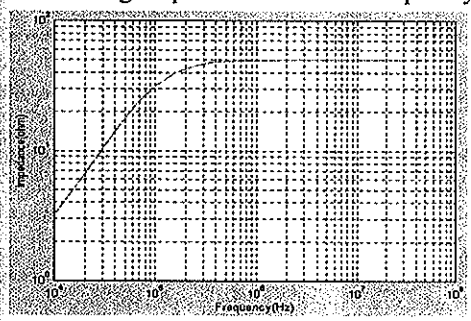


Terminating Impedance Seen by SMPS

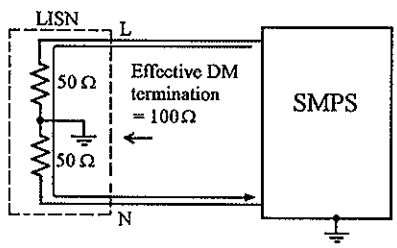


$$Z_L(j\omega) = \frac{j\omega L_1 (R + 1/j\omega C_1)}{j\omega L_1 + (R + 1/j\omega C_1)} = \frac{-\omega^2 L_1 C_1 R + j\omega L_1}{-\omega^2 L_1 C_1 + j\omega R C_1 + 1}$$

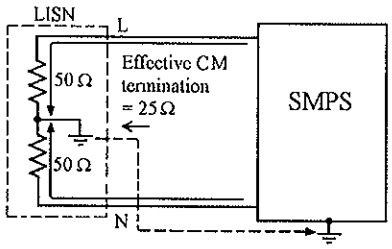
Terminating Impedance Versus Frequency



Effective DM LISN Termination



Effective CM LISN Termination



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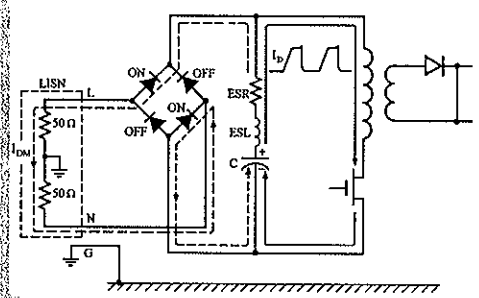
DM Conducted Emissions



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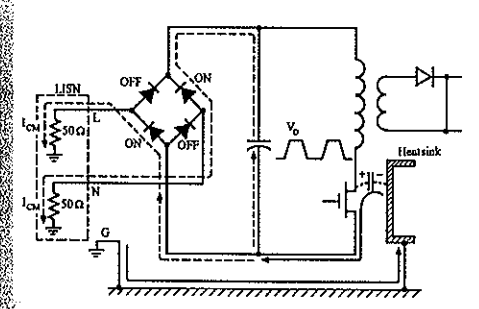
CM Conducted Emissions



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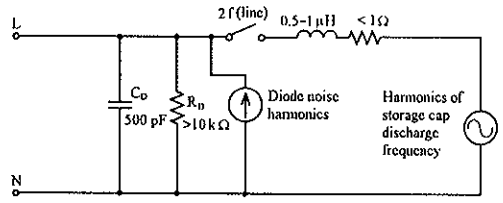
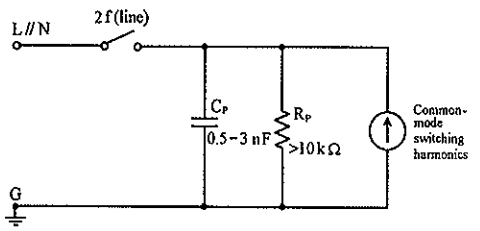
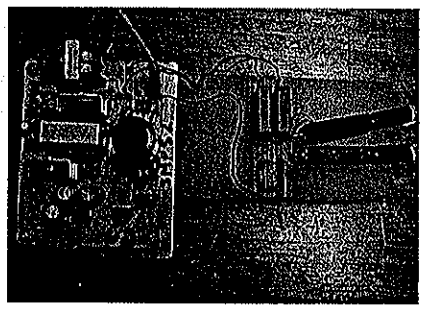
Equivalent DM Noise Source



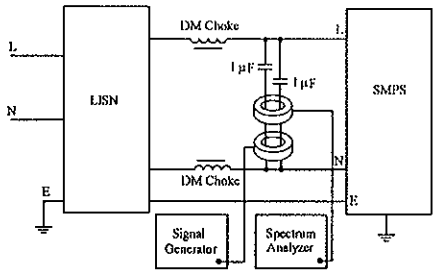
Equivalent CM Noise Source



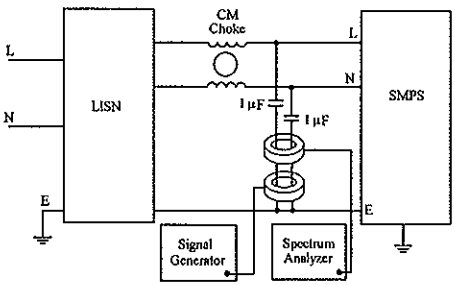
Noise Source Impedance Measurement



DM Noise Source Impedance Measurement



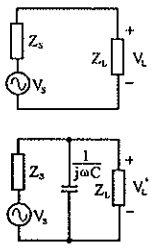
CM Noise Source Impedance Measurement



Typical CM and DM Source impedance

	CM	DM			
	Capacitance	Rectifier on-state		Rectifier off-state	
SMPS #1	130 pF	120 nH	0.87 Ω	130 pF	20 k Ω
SMPS #2	37 pF	150 nH	1.41 Ω	40 pF	25 k Ω
SMPS #3	1000 pF	80 nH	1.17 Ω	30 pF	20 k Ω

Shunt Capacitor as Low-Pass Filter



$$A = \frac{V_L}{V_L'} = \frac{V_L/V_S}{V_L'/V_S}$$

$$= \left(\frac{Z_L}{Z_S + Z_L}\right)\left(\frac{Z_S + Z_L + j\omega C Z_S Z_L}{Z_L}\right)$$

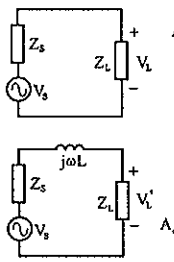
$$= 1 + \frac{j\omega C Z_S Z_L}{Z_S + Z_L}$$

$$= 1 + \frac{Z_P}{Z_{cap}}$$

$$A_{dB} = 20 \log\left(1 + \frac{Z_P}{Z_{cap}}\right)$$

where $Z_P = \frac{Z_S Z_L}{Z_S + Z_L}$ & $Z_{cap} = \frac{1}{j\omega C}$

Series Inductor as Low-Pass Filter



$$A = \frac{V_L}{V_L'} = \frac{V_L/V_S}{V_L'/V_S}$$

$$= \left(\frac{Z_L}{Z_S + Z_L}\right)\left(\frac{Z_S + Z_L + j\omega L}{Z_L}\right)$$

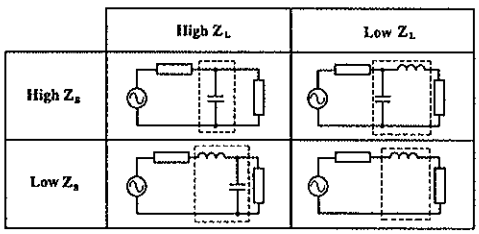
$$= 1 + \frac{j\omega L}{Z_S + Z_L}$$

$$= 1 + \frac{Z_{ind}}{Z_{sum}}$$

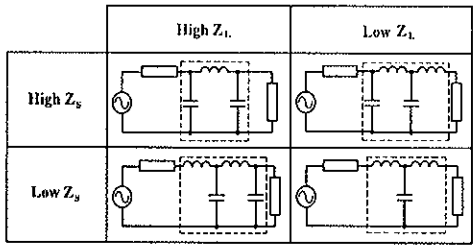
$$A_{dB} = 20 \log\left(1 + \frac{Z_{ind}}{Z_{sum}}\right)$$

where $Z_{sum} = Z_S + Z_L$ & $Z_{ind} = j\omega L$

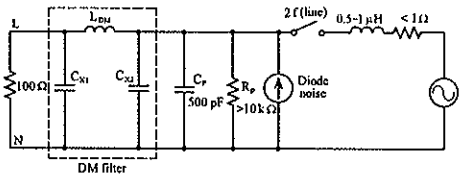
Effective Low-Pass Filter Configurations



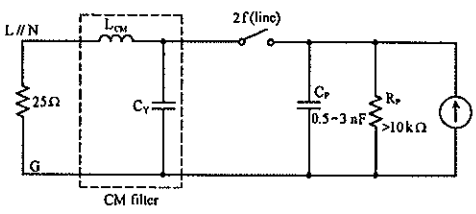
Higher Order Low-Pass Filter Configurations



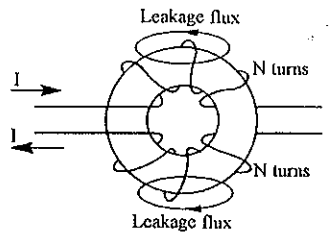
Equivalent DM Circuit For EMI Analysis



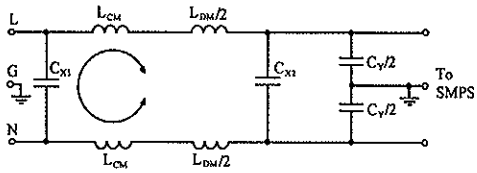
Equivalent CM Circuit For EMI Analysis



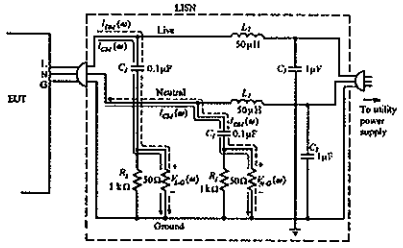
Common-Mode Choke



Integration of DM & CM Filters

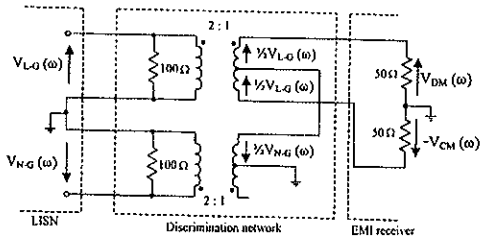


Measured Emissions in Live & Neutral

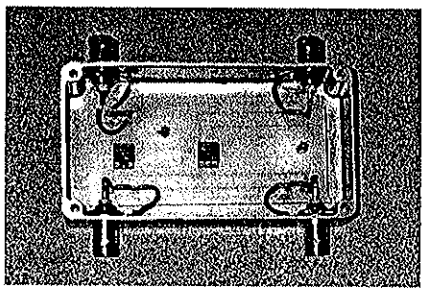


$$V_{L\text{-}G}(\omega) = [I_{CM}(\omega) + I_{DM}(\omega)] \times 50\Omega = V_{CM}(\omega) + V_{DM}(\omega)$$

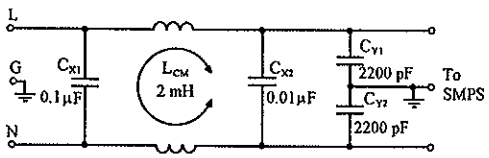
CM/DM Discrimination Network



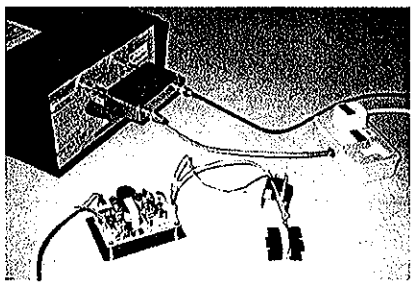
Self-made Discrimination Network



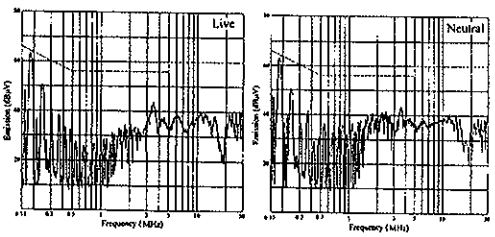
Case Study: Original Power Line Filter of a SMPS



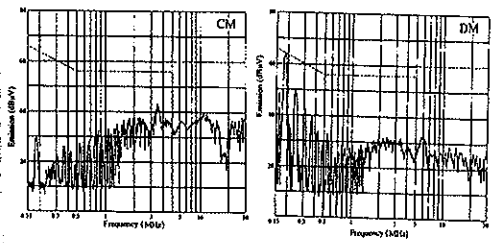
CM & DM Emissions Measurement



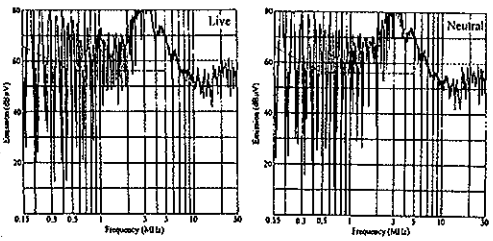
Live & Neutral Conducted Emissions With Original Power Line Filter



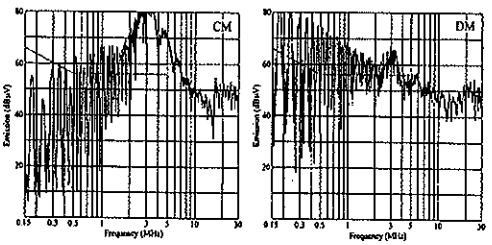
CM & DM Conducted Emissions with Original Power Line Filter



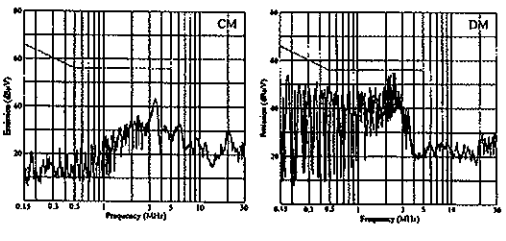
Live & Neutral Conducted Emissions Without Power Line Filter



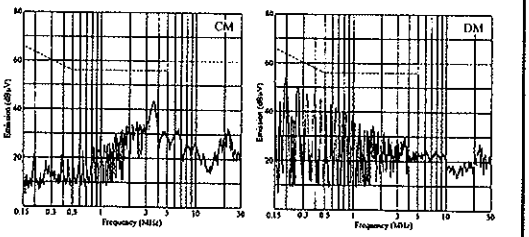
CM & DM Conducted Emissions Without Power Line Filter



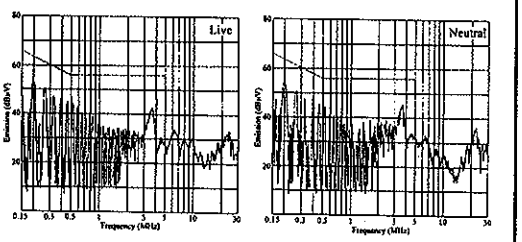
CM & DM Conducted Emissions With L_{CM} (2 mH) Added



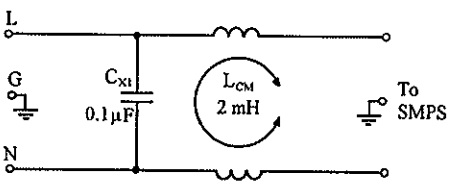
CM & DM Conducted Emissions With L_{CM} (2 mH) & C_{X1} (0.1μF) Added



Live & Neutral Conducted Emissions With L_{CM} (2 mH) & C_{X1} (0.1μF) Added



Minimum Number of Filter Components to Meet EMI Limits

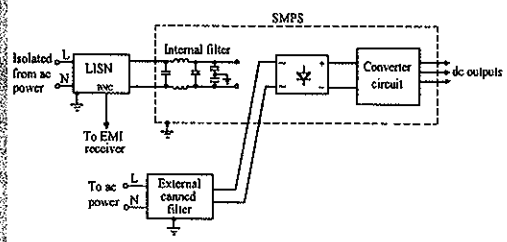


C_{X2}(0.01μF), C_{Y1}(2200 pF) and C_{Y2}(2200 pF) can be removed

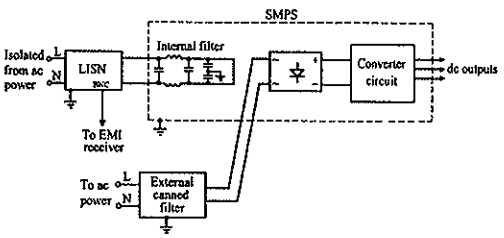
Near-Field Coupling to Power Line Filter

- The fields generated by SMPS are of near-field nature
- Effectiveness of the filter will be degraded if it pick up strong electric and magnetic fields
- Layout of filter on the PCB to avoid strong pick up of fields is a crucial issue

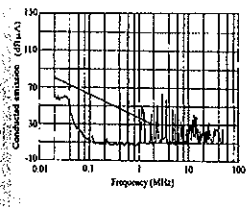
Identification of Electric Field Coupling

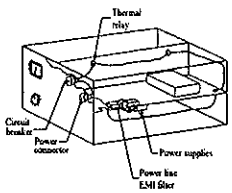


Identification of Magnetic Field Coupling

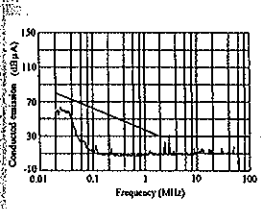


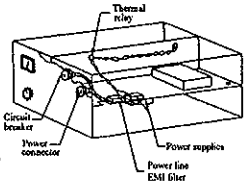
Magnetic Coupling to Large Wire Loop





Reduced Magnetic Coupling by Re-Wiring







Institute of
High Performance Computing

EMC Modeling and Simulation
Part I

Dr Lee ErPing

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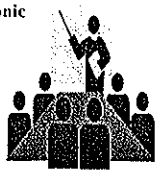
Institute of High Performance Computing
Singapore

19-20 April 2001

Outline

- EMC/EMI problems in high speed electronic design
- Electromagnetic modeling Techniques
- Modeling preparation
- Creating EMC/EMI Models



1. EMC/EMI Problems in Electronic Design

- The Technology Trends
- Component characteristics at High frequency
- High Speed electronic design problems
- Why use simulation
- Benefits by using simulation technologies

The Needs for EMC/EMI Analyses

Technology Trends

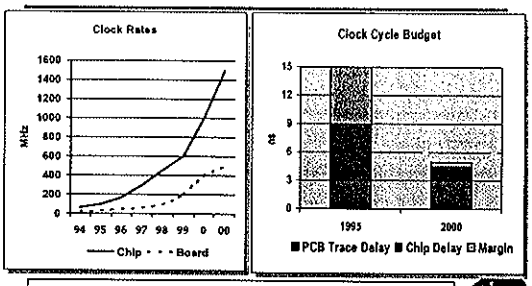
- Fast Clock speed (2001)
  - 1995
    - Processor Speeds 100 MHz
      - Clock skew requirements ± 700ps
    - Bus Speeds 66 MHz
    - PCI bus
    - <20% of nets are high speed

  2001
  1500+MHz
  ± 125ps
  >150MHz
  >60% of nets are high spped
- Deep-submicron (0.07 μm)
- High denser board
- Shorter product-to-market cycles and end-product price pressure





What's the Problem?



Will the design work at intended speeds under all conditions?

Europe

- The EMC Directive (336/EEC)
  - Immunity from ESD; RF-radiated interference (RFRI); RF-conducted interference (RFCI), which enters products via power and signal lines
  - electrical surges, usually resulting from lightning strikes to power or telephone lines;
  - electrical fast transients (EFTs), or bursts, which usually result from arcing of switch contacts that open while current is flowing

USA and Asia

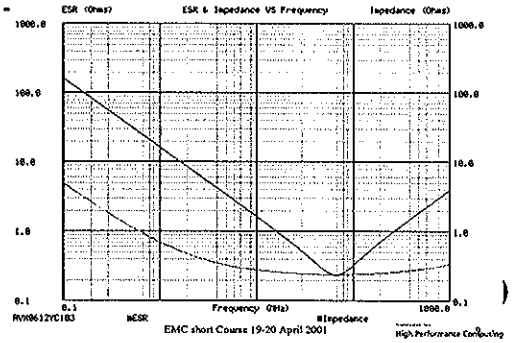
- The US Federal Communications Commission's RF-emissions requirements parallel the EMC Directive
  - FCC guidelines for radiated and conducted EMI
  - Manufacturers can legally sell products in the United States only if those products comply with the applicable regulations
- Japan, VCCI
- Taiwan, EMC regulatio
- Mil-standard

How Wires Behave at High Frequencies



- At low frequencies, an ordinary wire will effectively short two circuits
- At high frequencies, only a wide, flat object can short two circuits
- A wire has too much inductance to function as a short at high frequencies

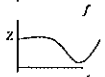
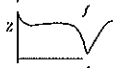
Frequency Response of A 10 pf Capacitor



Propagation Delay of EM fields in Various Media

Medium	Delay in picosec/inch	Dielectric constant
Air (radio waves)	85	1.0
Coax cable (66% velocity)	113	1.8
Coax cable (66% velocity)	129	2.3
Silicon dioxide	168	3.9
FR-4 PCB (outer trace)	140 – 180	2.8 – 4.5
FR-4 PCB (inner trace)	180	4.5
Alumina PCB (inner trace)	240-270	8.0 – 10

Component Characteristics at High Frequencies

Component	Low frequency Behaviour	High frequency behaviour	Response
Wire			
Resistor			
Capacitor			
Inductor			

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Component Behaviour at High Frequencies

- **Capacitance**
  - Draw surges of drive current, and causes reflections on long lines
- **Inductance**
  - Causes ground bounce and power supply noise
- **Mutual capacitance**
  - Causes crosstalk between high impedance circuits
- **Mutual inductance**
  - Causes crosstalk in connectors and in bad layouts
- **Skin effect resistance**
  - Limits speed of copper-based communication systems

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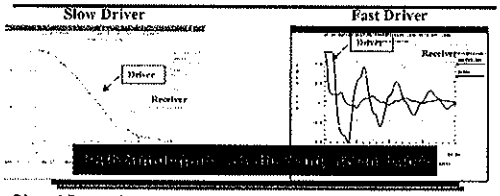
High-Speed Design Challenges



- **Signal Integrity**
  - Reflections, ringing, overshoot, monotonicity
  - Crosstalk
  - Simultaneous switching noise
- **Timing**
  - Meet setup/hold requirements
  - Path level delay management
  - Clock distribution and skew

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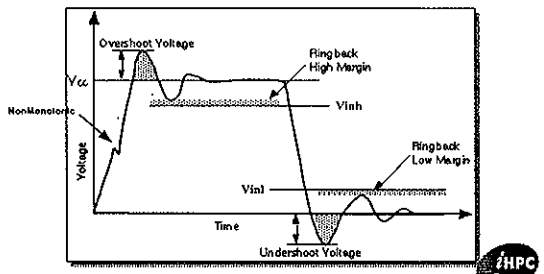
Terminology

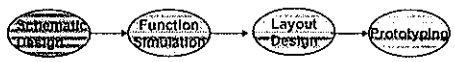


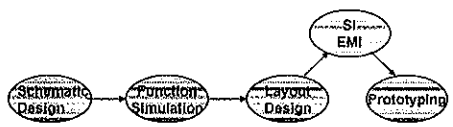
Digital Circuits at High Speed & Low Supply Voltage

- Noise margins
- High speed signals: knee frequency, breakpoint frequency
- Component and wire behaviours at high frequency
- Electrically long traces and guided wave propagation (TEM)
- Ground noise
- Power supply noise
- Reflection and ringing
- Crosstalk
- Electromagnetic interference (conducted and radia
- Electromagnetic compatibility

High Speed Design

Low speed Design





High speed Design

EMC/EMI Problems

- Expected emission from a system
- Susceptibility of a system
- Propagation of disturbances
- Coupling between cables
- Coupling between antennas and cables
- Electric and magnetic field distribution on conductive or dielectric structures
- Antenna performance covering gain, antenna factors, radiation patterns, input impedance and RADHAZ assessment
- Shielding performance of complex structures

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Signal Integrity Issues

- Ringing and reflection
  - Caused by load and trace impedance mismatches (termination)
- Crosstalk
  - Faster switching creates more crosstalk (separation and ground plane)
- Ground bounce
  - Shorter rise times have higher di/dt, which causes more ground bounce inside packages
- Power-ground noise
  - Capacitive loads causes bigger current surges at faster switching speeds; these surges cause more power-ground noise
- EMI noises

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Critical Design Requirements

- Managing the bus designs
  - Stringent timing and signal integrity requirements
  - Dealing with source synchronous, pipelined busses Crosstalk
- Crosstalk
  - Managing noise margins
  - Effects of crosstalk on timing
- Clock Distribution
  - Shrinking skew requirements
- Modular Design
  - Multiboard analysis of critical system-level signals
  - CPU modules, memory modules, connectors, etc

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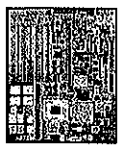
PCB and IC:



- Timing analysis
- Signal Integrity Analysis
  - Reflection and ringing
  - Crosstalk
  - Power/ground bounce



- EMI/EMC
- Thermal
- Vibration & shock
- Fatigue



Why Using Simulation

- High speed and complex component applied, traditional PCB techniques
  - not effective for proper signal and compliance analysis
  - take much long design and testing time
  - not cost effective
- Using specific integrated circuits gives new and challenging problem for traditional techniques
- Simulation would provide the optimization solution and performance
- single PCB design complies with the EMC requirement, but does not means the assembly

Why using simulation (cont'd)

- Experts commented that nowadays electronic design to meet modern EMC requirements without many iterative redesign is impossible(Plexus, USA 1999)
- Many cases evidenced product will not pass all the EMC tests on 1st or 2nd attempt, many iterations of rework and retest are required.
- EMI now can be modeled and analysed during design phase, cost effective Emi mitigation can be included in the first prototype (USA, Plexus, 1999)
- Designers Recommended to approach the EMC experts for during design phase avoiding to many iterative redesign and retest.

The Advantages

- .to achieve maximum performance in a cost-critical product.
- to achieve electrically correct designs in one pass
- easily and quickly evaluating the effectiveness of design changes, detecting and correcting EMC/EMI and SI problems before prototyping,
- improving the product quality and shorten the design cycle and time to market and;
- save significantly on time, rework, and board spins
- reducing the design costs.

2. Electromagnetic Modeling Techniques

- The moment of method
- The Finite Element method
- The finite differential time domain methods

Maxwell Equations

- $\nabla \times H = J + \partial D/\partial t$ $\quad \nabla \times H = \sigma E + j\omega\varepsilon' E$
- $\nabla \times E = -\partial B/\partial t$ $\quad \nabla \times E = -j\omega\mu H$
- $\nabla \bullet B = 0$ $\quad \nabla \bullet (\mu H) = 0$
- $\nabla \bullet D = \rho$ $\quad \nabla \bullet (\varepsilon' E) = \rho$

- E, H, D, B, J, ρ, ε', μ, and σ are functions of r. Use constitutive relations: $J = \sigma E$, $D = \varepsilon' E$, $B = \mu H$
- Assume time dependence $E(r,t) = E(r) \exp(j\omega t)$ and similar for H, D, B, ρ, J.
- H, D, B, J, ρ, ε', μ, and

Numerical techniques

- *The method of moment (MOM)*

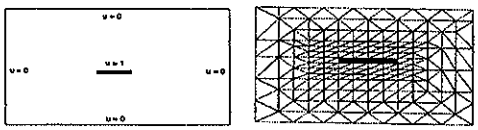
  MOM is a surface current technique from which a set of linear equations for RF surface current can be formulated. MOM with standard computer codes can model metal and air very efficiently, but not for dielectric and other material by using. It is a frequency domain solver.

The finite element method (FEM)

- **FEM is a volume-based solution technique, and the solution space is split into small elements and the field in each element**
- **is approximated by low-order polynomials with unknown coefficients. A system of equations can be derived from a variational expression reduced from Maxwell's equations.**

Finite Element Method

- **Take an example to solve the field distribution of a shielded micro strip transmission line using FEM**
- **It can be expressed by Laplace Equation:**
- **$\nabla^2 u(x,y) = 0$ at 2-Dimension**



Configuration of a shielded microstrip transmission line

FEM Mesh

Numerical techniques

- *The finite-difference time-domain method (FDTD)*

FDTD is a volume-based solution to Maxwell's differential equations, where Maxwell's equations are converted into central difference equations and are solved directly in the time domain. It has become increasingly popular for computations of electromagnetic wave propagation and scattering problems, electromagnetic biological effects.

Mathematical Principle of the FDTD Method

- Basic finite-difference equations

a direct integration of Maxwell's time-dependent curl equations.

$$\nabla \times \vec{H} = \vec{J} + \partial \vec{D}/\partial t \quad (1a)$$

$$\nabla \times \vec{E} = -\partial \vec{B}/\partial t \quad (1b)$$

In Yee's cell

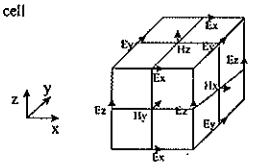


Fig. 1 Yee's cell in 3-D FDTD simulation.

Mathematical Principle of the FDTD Method

A series of finite-difference equations can be developed on Yee's cell in the form that E- and M- field are staggered in space and time. For example, *x*- component of electrical field is

$$E_x^{n+\frac{1}{2}}(i,j,k) = E_x^{n-\frac{1}{2}}(i,j,k) + \frac{\Delta t}{\varepsilon}\left\{H_z^n\left(i,j+\frac{1}{2},k\right) - H_z^n\left(i,j-\frac{1}{2},k\right)\right\}\Delta y - \left\{H_y^n\left(i,j,k+\frac{1}{2}\right) - H_y^n\left(i,j,k-\frac{1}{2}\right)\right\}\Delta z \quad (2)$$

- Courant's condition

This constraint exerts on temporal step and spatial steps

$$\Delta t \le \frac{1}{\sqrt{\frac{1}{\Delta x^2} + \frac{1}{\Delta y^2} + \frac{1}{\Delta z^2}}} \quad (3)$$

Mathematical Principle of the FDTD Method

- Absorbing boundary conditions
  - *Reason: simulate open domain EM environment*
  - *Different kinds of ABCs*
    - ✓ Differential-equation-based ABCs
      - ☐ a dispersive ABC
      - ☐ Higdon's ABC
      - ☐ Mur ABC
    - ✓ Material ABCs
      - ☐ Perfectly matched layers

Mathematical Principle of the FDTD Method

- ✓ Other ABC's
  - ☐ Liao's ABC
  - ☐ Superabsorption
- Near- to far- field transformation technique

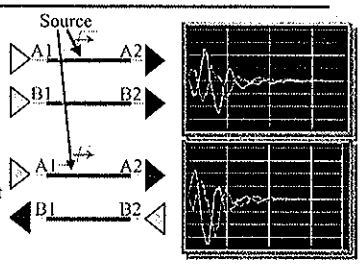
Reason: because of the availability of computer resource, normally only can near EM field be calculated by using the FDTD method. This technique is needed if far field parameters, such as antenna's pattern, gain, is required.

3. Preparation Modeling

- **Modeling EMI is to accurately predict the system emission to be acceptable level, and to eliminate the interference,**
- **All EMC problem modeling can be broken into 3 parts:**
  - **the sources of the energy**
  - **the radiation mechanism**
  - **the means by which it couples from the source to the radiation mecahnism**

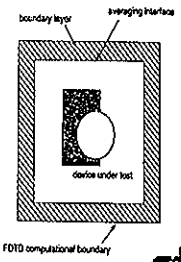
To identify the Sources

- The Emi sources are intended and unintended RF sources that couple to a conductor/com ponent where it can cause problems.



Geometry Modeling

- **FDTD Modeling**
- FDTD computational domain
- It is split into two domains
- Interior region
- and a boundary layer



Input Information for Circuit EMI Analyses

- **Input Information for Circuit EMI Analyses**
- Schematic
- Layout
- Material Parameters and geometry of the PCBs and connectors
- Driver and Receiver's IBIS Model or SPICE Model
- Frequency of operation

Pre-route analysis

- Determine and verify placement and routing rules for EMC and SI
- Decide optimal conductor sizes and spacings
- Simulate critical traces and connectors with partially routed board
- Select dielectric and conducting materials
- Decide thickness of dielectric layers
- Decide power and ground plane locations
- Decide via geometry and size
- Determine maximum allowable trace lengths to ensure time delay

Selecting of computational techniques

- To define the technique to be used
  - Quasi-static technique

    To be used to solve the problems where the geometry is smaller compared to the wavelength

  - Full wave technique

    provide a complete solution to Maxwell's equations within the computational space for all conductors and materials

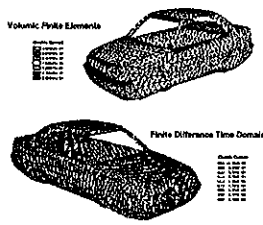
    - Two techniques
      - Time domain techniques
      - Frequency domain techniques

Selecting of computational techniques

- Three common simulation techniques
  - Finite differential Time domain
  - Finite Element Method
  - Moment method (frequency domain)

Finite Element Modeling of a Car

The electric field in a car



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Output of SI/EMR analyses

- **Transmission line parameters**
- **crosstalk and reflection**
- **'what if' analysis**
- **radiation spectrum**
- **far and near field scans**
- **radiation patterns**
- **frequency dependent R, L, C and G parasitics for trace, via, and power and ground planes**
- **simultaneous switching noise analysis**
- **power and ground bounce detection**

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Causes and Effects

Modifications	Effects
Components' Placement, Trace's Width, Layer's Height	Propagation delay
Medium's permittivity	Characteristic Impedance
Spaces between Traces	Crosstalk Noise
Routing	Impedance Match and Crosstalk Noise
Component's Type	Impedance Match
Proper Termination	Impedance Match

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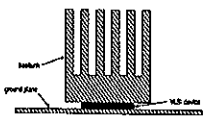
4. Creating EMI/EMC Models

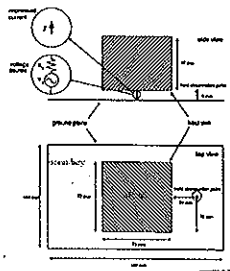
- Creating a practical EMC/EMI model is most important to ensure the accurate physical model, but not require excessive computer resources.
- Creating EMC/EMI models by using FDTD shall follow these procedure:
  - 1. Define the required cell size for the model
  - 2. Select the absorbing boundary conditions
  - 3. Define the size of the computational domain
  - 4. Enter the p|problem geometry and material characteristics
  - 5. Add source
  - 6. Add observation points , including any field extension requirements

Example: Creating EMI/EMC Models Heat Sink Model

- Heat Sink Problem geometry
- Boundary size
- 144x192x54mm

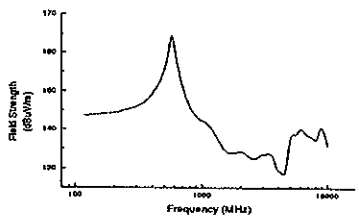


Side view of a VLSI device and a heatsink on top of a ground plane



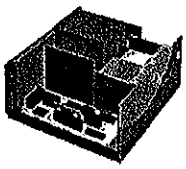
Near Field simulated by FDTD

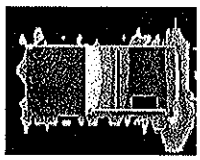
- Near Field simulated by FDTD



MEI Modeling of PC

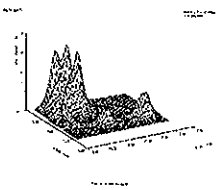
Emission from a PC



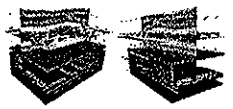


Electronic circuit modeling

- PCB radiation analysis field scan

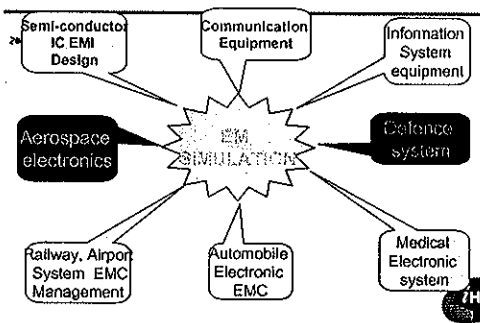


The Electronic Circuit Example



Electronic circuit electric field

EMC simulation APPLICATIONS





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EMC Modeling and Simulation

Part II -Reduction of By using Simulation

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Institute of High Performance Computing

Singapore

19-20 April 2001

Outline

- Signal integrity at high speed PCB design
  - Transmission line,
  - Reflection
  - Crosstalk
- Component Modelling, IBIS models
- EMI/EMC simulation
- Summary



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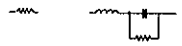
Signal Integrity-
Transmission Line Impedance

- A copper trace at printed circuit board(PCB) will be a transmission line for signal transmission
  - Strictly speaking, any conductor carrying an electric signal is a transmission line. Generally, the term transmission line has come to mean a conductor of a high speed signal. e.g., a wire, coax cable or PCB traces.
- Transmission line at low frequency , it is resistive
- Transmission line as high frequency, it is reactive by L and C

Low frequency High frequency



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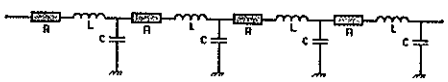
Transmission Line Impedance

- PCB trace can use the following equivalent R,L,C circuit



$Z=\sqrt{\frac{L}{C}}$

L: inductance per unit length
C: capacitance per unit length

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Types of Transmission Line

- Although it's difficult to calculate L and C, a few important facts are still visible:
- The wider the trace, the higher the C, and the lower the Z
- The smaller the distance between the plates, the higher the C and the lower the Z
- Transmission line in the scope here, can be categorised as: Micro-stripline & Stripline



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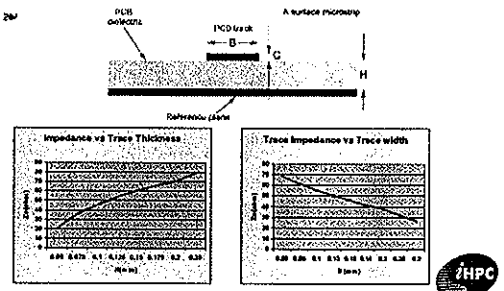
Trace Impedance



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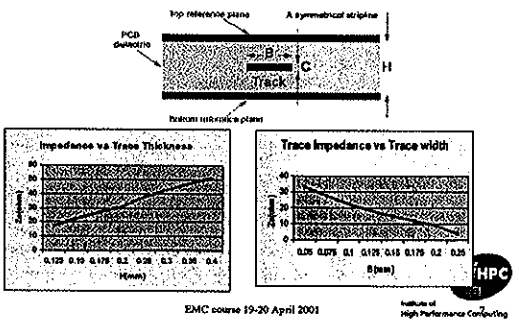
Stripline Impedance



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Critical Length for SI and EMC

- The term 'High signal speed' means:
  - high edge rate
  - or high clock rate
- The 2-way delay of the line must not be longer than the rise time of the signal. Otherwise, unbearable reflection and ringing will appear as overshoot and undershoot.

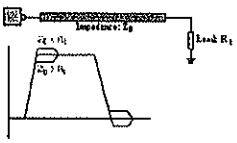
$$Tr \le \frac{2 \times TraceLength}{v_p}$$

Tr: rise time of the driving signal
vp: wave propagation velocity
e.g.: in FR4 PCB, vp=15cm/ns

In fact, this technique should be used for even shorter traces, e.g.:For Tr=3ns, Critical length=5cm (and possibly less)

SI:Reflections

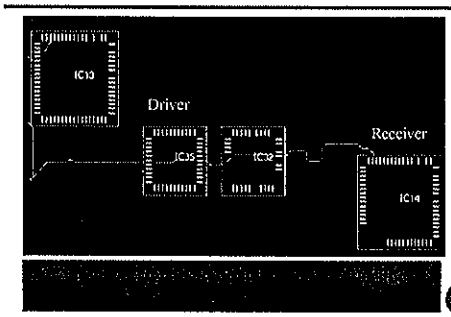
- Reflections due to impedance mismatch on long nets
- If a net is shorter than the critical length, the reflections are normally below 10 - 15%, no matter what impedance the line and the receiver have. If the net is longer however, a substantial amount of the signal is reflected back towards the driver if the line impedance and the input impedance of the receiver does not match.



•The reflection coefficient is expressed in percent. If the reflection coefficient is 50%, it means that half of the signal is reflected back to the driver instead of being absorbed by the receiver.

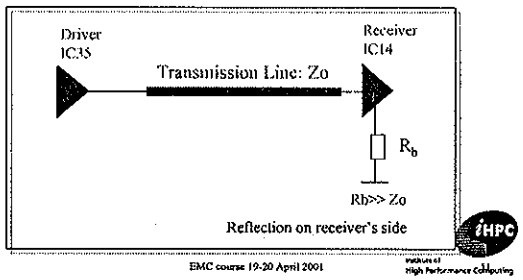
$$K_{refl}=100\frac{R_T-Z_0}{R_T+Z_0}$$

SI: Reflection Simulation



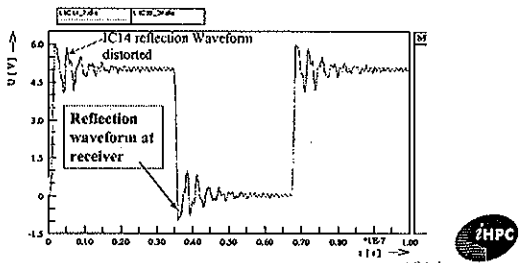
Equivalent Circuit

Equivalent circuit from driver IC35 to receiver IC14
Line impedance does not match termination impedance Rb



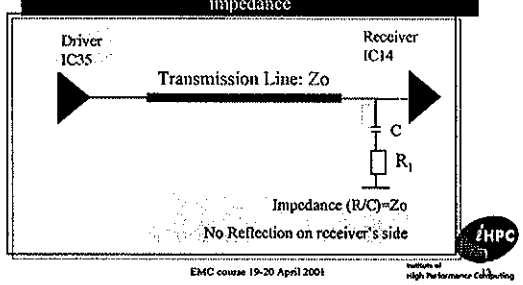
Reflection Voltage

Reflection on receiver IC14 due to improper termination



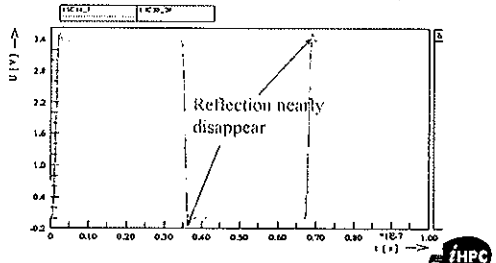
Equivalent Circuit

Equivalent circuit from driver IC35 to receiver IC14
with pull-down R-C at the receiver to match termination impedance



Reflection Voltage

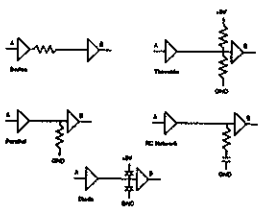
SI behavior with correct R-C receiver termination



Reduction Reflections with Termination

- Use a terminator to absorb the energy in the signal wave
- Termination is a vital part of high speed design, but if you can, try to keep the trace (and cable) length short, so that you may not need terminations. The side effects of terminations add delay, add to power consumption, and add cost; but sometime termination are unavoidable.

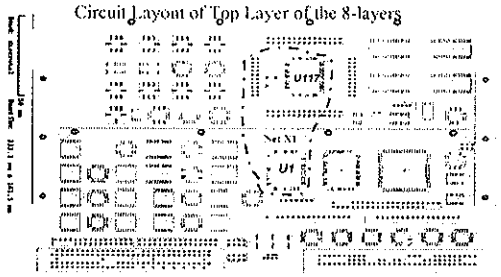
Termination



- Series termination resistor
- Parallel termination resistor
- Thevenin network
- RC network
- Diode network

Signal Integrity and Electromagnetic Simulation of a High Speed digital 8-layer I/O PCB with an embedded Microcontroller

Circuit Layout of Top Layer of the 8-layers



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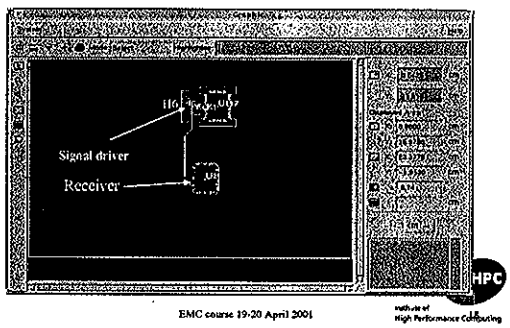
Net X1 of PCB



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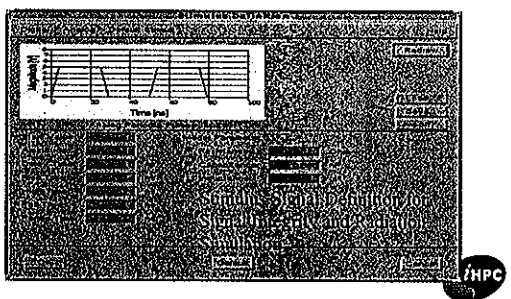
Reflection Analysis
Stimulus Signal



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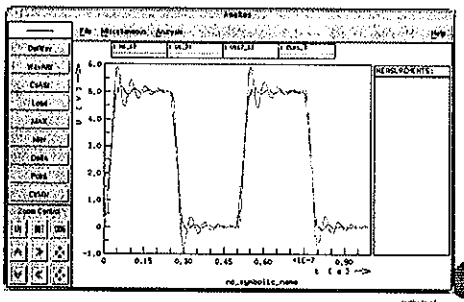
Reflection Voltage for Net X1



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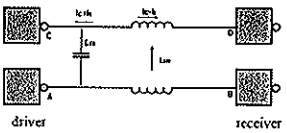
SI: Crosstalk

- Crosstalk: the energy is coupled from one or more transmission lines to an adjacent transmission line.
- Crosstalk is an unintended EM coupling.
- **I.e. Send a pulse from the driver A to the receiver B, the signal is capacitively coupled into the line C - D. The two traces also have a mutual inductance(Lm) causing inductive coupling of current.**



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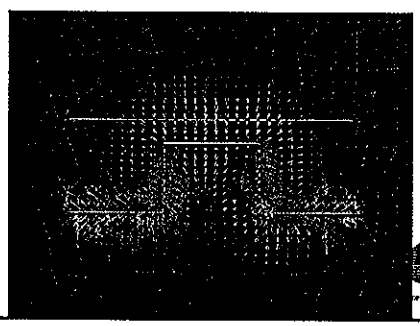
SI: Crosstalk

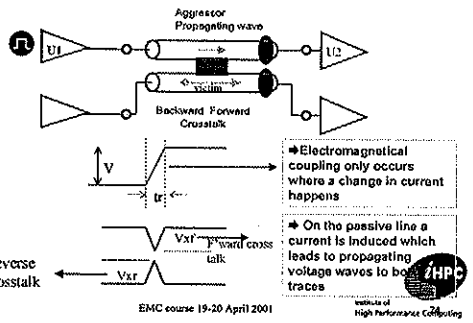
Electromagnetic Coupling between adjacent lines



Cross talk -coupling dependent

- Geometry of the trace
  - distance between the traces, closer the trace, the worse the crosstalk
  - thickness, width of the traces
  - coupled length
  - distance to the reference plane
- Signal driver rise and fall time
- Dielectric material
- Track shielding can reduce coupling, but not cost-effective in digital design
- Coupling is described by L',C' matrices (lossless case)

Two kinds of cross talk: Forward vs. Reverse



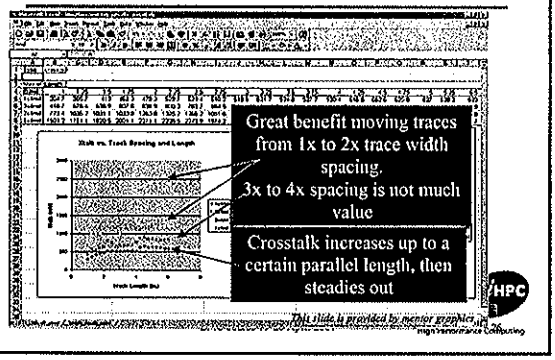
➡Electromagnetical coupling only occurs where a change in current happens

➡ On the passive line a current is induced which leads to propagating voltage waves to both traces

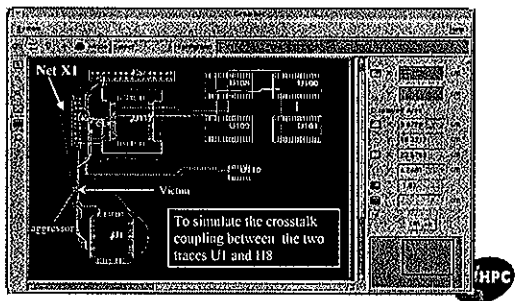
Crosstalk:Forward vs Reverse

	Forward xtalk	Reverse xtalk
Direction	Same as the aggressor	Opposite of the aggressor
Polarity	Opposite to aggressor wave	Same as aggressor wave
Crosstalk voltage	$Vxf=K_f(V/t_r)*length(coupling)$	$Vxr=Kr\ V$ for $length>S_p t_r/2$
		$Vxr=Kr\{(2/S_p)(V/t_r)\}$ For $length(l)<S_p t_r/2$
	(S_p:signal propagation speed)	
	Crosstalk voltage decreases with distance	Crosstalk voltage decreases with distance

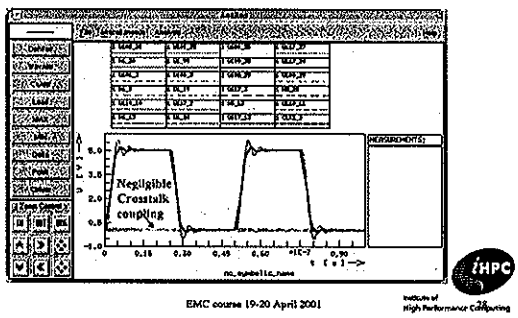
Crosstalk vs. Trace Spacing



Cross Talk Simulation



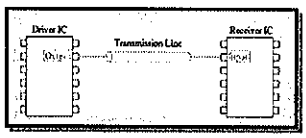
Cross-Talk Simulation



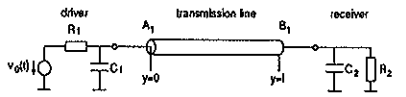
Crosstalk Control

- Use low impedance traces and terminate properly.
- Use short traces to reduce the coupling length
- Use thin lamination between the conductors and the ground/power plane.
- Slowdown signal rise/fall time
- Trace spacing=3 x width of the trace

Component Modelling



- Models are used for each IC pin connected to the net of interest



Macromodel diagram

Component Modelling

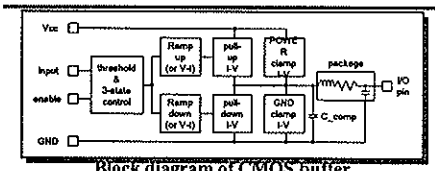
- SPICE
- IBIS (I/O Buffer Information Specification)
- Measurements
- 'Other techniques'
  - Substitute models
  - Linear models
  - Combination of known data and/or assumptions

IBIS Model

I I/O
B Buffer
I Information
S Specification

- IBIS is a standard for describing the behavior of I/O buffers in plain ASCII text format
  it is really not a model, it is a data format specification to simplify modeling and model data exchange
- Started in the early 90's to promote tool independent I/O models for system level Signal Integrity work
- Almost all simulation tool vendors support it today
  Quad, Cadence, Interconnectix, Incases, Hyperlinx, HSPICE, etc.

Building blocks of a basic IBIS model



Block diagram of CMOS buffer

A basic IBIS model consists of:

four I-V curves: - pullup & POWER clamp
- pulldown & GND clamp

two ramps: - dV/dt_rise
- dV/dt_fall

die capacitance: - C_comp

packaging: - RLC values

for each buffer on a chip

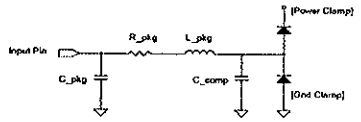
Source of IBIS Model

How to obtain IBIS Model :

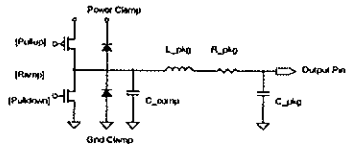
- **Provided by IC designer**
- **Free models on the website**
- **Convert from SPICE to IBIS**
- **Buy from several overseas companies, but expensive**
- **Measurement**

Typical IBIS Input(Receiver) Model

- C-pkg: Package capacitance
- R-pkg: Package resistance
- L-pkg: Package inductance



Typical IBIS Output(driver) Model



sample AM186ES.IBS model with IBIS version 2.1.

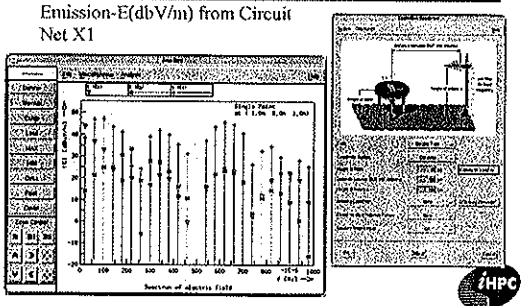
```
[IBIS Ver]  2.1
[File Name] am186es.ibs
[File Rev]  1.0
[Date]      Wed Jul  1 12:33:10 1998
[Source]    Jon Powell (ViewCD)
[Disclaimer]  Data is for modeling purposes only and is not guaranteed
[Copyright]   NOT IMPLEMENTED TBD
[Component]     am186es
[Manufacturer]  AMD
[Package]
| variable       typ        min       max
R_pkg            122.50m    NA        NA
L_pkg            10.33nH    NA        NA
C_pkg            0.02pF     NA        NA
[Pin] signal_name    model_name                    R_pin L_pin  C_pin
1     AD(0)          iobpad_BI                     122.50m 10.33nH  0.02pF
2     AD(8)          iobpad_BI                     122.50m 10.33nH  0.02pF
3     AD(1)          iobpad_BI                     122.50m 10.33nH  0.02pF
4     AD(9)          iobpad_BI                     122.50m 10.33nH  0.02pF
5     AD(2)          iobpad_BI                     122.50m 10.33nH  0.02pF
6     AD(10)         iobpad_BI                     122.50m 10.33nH  0.02pF
7     AD(3)          iobpad_BI                     122.50m 10.33nH  0.02pF
8     AD(11)         iobpad_BI                     122.50m 10.33nH  0.02pF
9     AD(4)          iobpad_BI                     122.50m 10.33nH  0.02pF
10    AD(12)         iobpad_BI                     122.50m 10.33nH  0.02pF
11    AD(5)          iobpad_BI                     122.50m 10.33nH  0.02pF
12    GND            GND                           122.50m 10.33nH  0.02pF
13
```

EMI/EMC Simulation

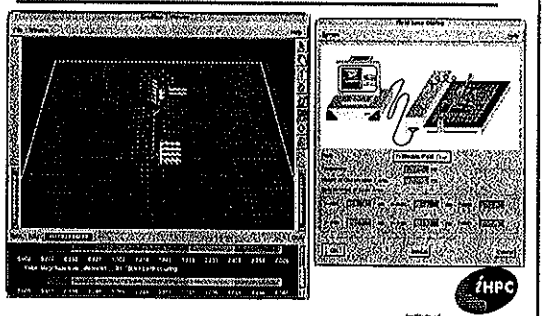
- Electromagnetic radiation from the PCB trace is solved using electromagnetic field solver moment of method
- Solver based on virtual measurement
- Check against legislations
- EMC simulation helps to solve EMC problems in an early design stage

Electromagnetic Radiation Simulation

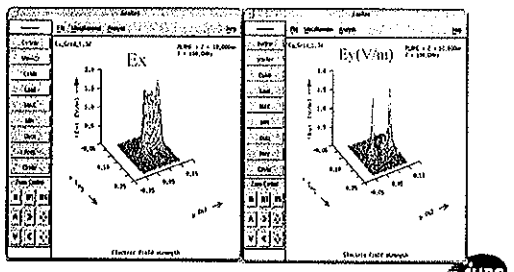
Emission-E(dbV/m) from Circuit Net X1



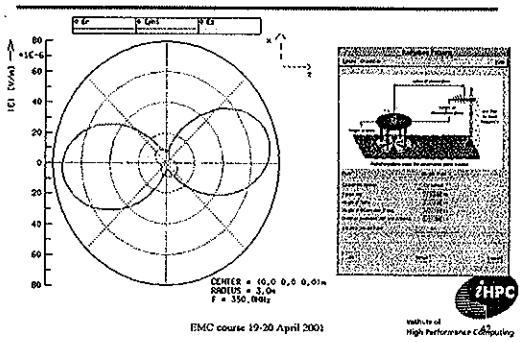
Near Field Scan



Electric field strength along the net

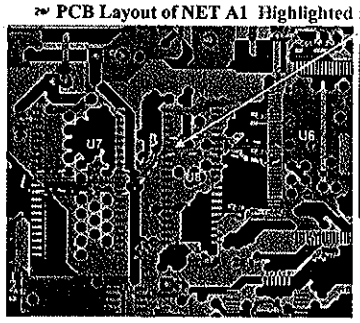


Radiated Emission Analysis: Radiation Pattern



Radiated Emission Example(2): A Printer Card

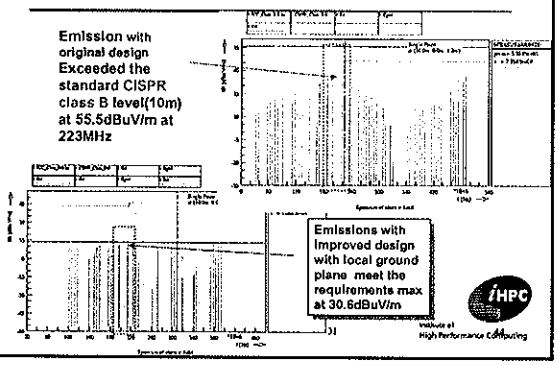
PCB Layout of NET A1 Highlighted : Critical Net A1



Stimulus Definition:
Tr = 3ns
Clock Frequency = 5.325MHz
Amplitude = 4.8V
High Time = 112ns
Source R = 10 Ohm
Source C = 5 pF

Radiated Emission Reduction of a Printer Card

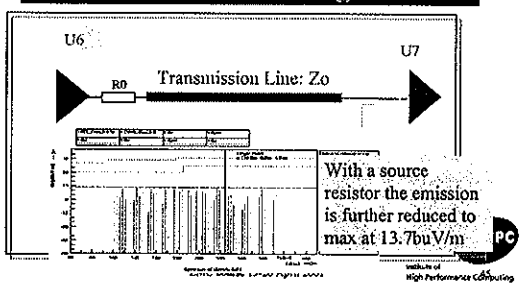
Emission with original design Exceeded the standard CISPR class B level(10m) at 55.5dBuV/m at 223MHz



Emissions with improved design with local ground plane meet the requirements max at 30.6dBuV/m

Radiated Emission Reduction of a Printer Card

Improved design with source terminated with resistor to absorb the radiation energy



With a source resistor the emission is further reduced to max at 13.7buV/m

EMI design practices

- reduce EM radiation
- reduce cross talk
- reduce reflections
- use slowest edge rate components
- use shortest possible return current path
- route high speed traces on internal layers
- partition high speed circuitry away from I/O
- avoid gaps in cable shielding

Signal Integrity(SI) vs EMI problems

- Majority EMI problems caused by Signal Integrity such as ringing, crosstalk
  - ringing can cause high frequency signal
  - crosstalk can cause increased I/O radiation
- SI could cause malfunctioning of the PCB
- SI can be easily simulated and fixed by the following methods:
  - Reducing the crosstalk
  - controlling the trace impedance to match the input and output impedance
  - Using slow rise and fall time signal
  - selecting correct termination
- EMI is dependent on whole PCB's parameters, routing, layout, connector placement etc

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Advantages of Simulation over traditional solution

- Detecting and correcting SI and EMC problems before prototyping
- to achieve maximum performance in a cost-critical product.
- to achieve electrically correct designs in one pass
- easily and quickly evaluating the effectiveness of design changes, detecting and correcting EMC/EMI and SI problems before prototyping,
- improving the product quality and shorten the design cycle and time to market and;
- save significantly on time, rework, and board spins
- reducing the design costs.

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Summary

- PCB simulation requires large capacity computer facilities
- PCB simulation is feasible and applicable today
- Simulation can eliminate 70% EMI problems
- Managing EMC can be a complex task
- EMI simulation tools are still under development
- Simulation can reduce the design time and improve the quality
- By pre-diagnosing the possible EMC problems on PCB, it enhances the ability in the success of designing a product. Design cycle time will get shorter. Therefore the cost will be lowered and efficiency to manufacture the product will be increased.

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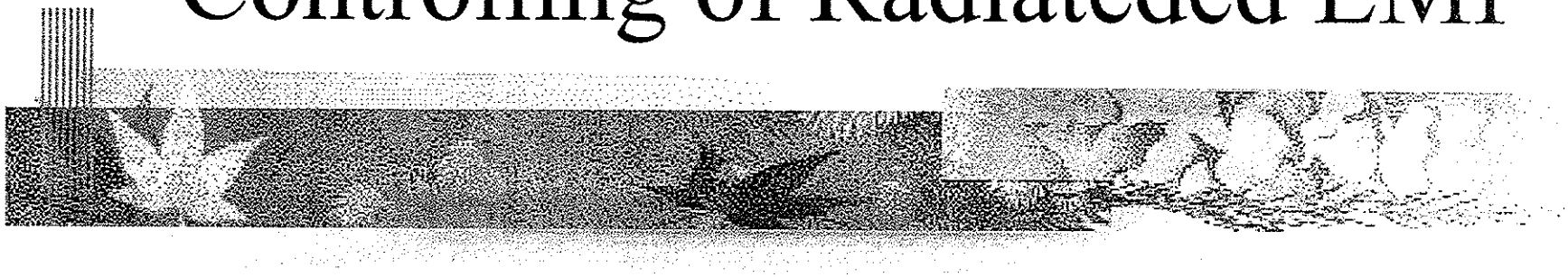
Controlling of Radiateded EMI



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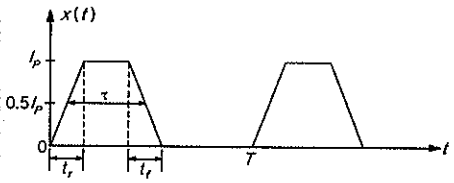
Nanyang Technological University

Major Sources of Radiated EMI

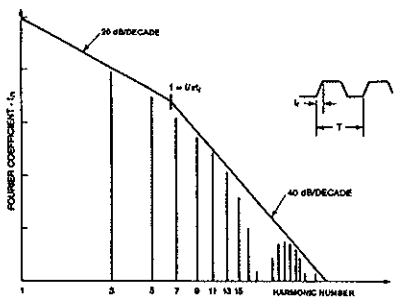
- Digital design is not just simply logic design of ones and zeros
- A digital circuit with ever increasing clock speed is also a radio frequency system with noise and interference potential
- The layout of digital circuits on PCB is the most important aspect of the ability of a product to meet radiated EMI requirements

Spectral Contents Periodic Pulses

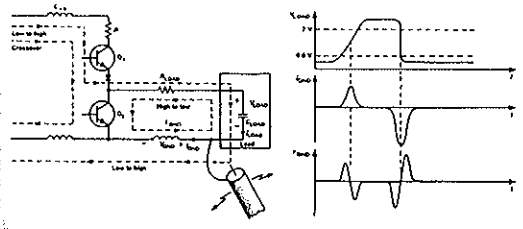


$$|C_n| = 2I_p \frac{\tau}{T} \left| \frac{\sin(n\pi\tau/T)}{n\pi\tau/T} \right| \left| \frac{\sin(n\pi t_r/T)}{n\pi t_r/T} \right| \quad \text{for } n \neq 0$$

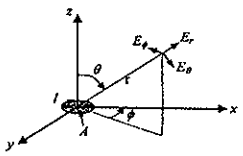
Spectral Envelope of Periodic Pulses



Radiation Mechanism of a Digital Circuit



Radiated Electric Field from a Loop



$$E_r = 0$$

$$E_\theta = 0$$

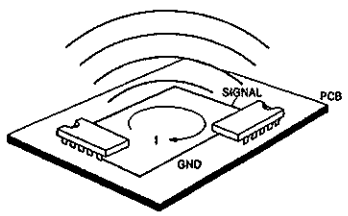
$$E_\phi = -j\frac{\omega\mu_o I A \beta_o^2}{4\pi}\sin\theta\left(j\frac{1}{\beta_o r}+\frac{1}{\beta_o^2 r^2}\right)e^{-j\beta_o r}$$

where $\beta_o = 2\pi/\lambda$, $\lambda = 3\times10^8/f$

$$E_\phi = -j\frac{\omega\mu_o I A \beta_o^2}{4\pi}\sin\theta\left(j\frac{1}{\beta_o r}\right)e^{-j\beta_o r} \quad \because \frac{1}{\beta_o^2 r^2} \approx 0$$

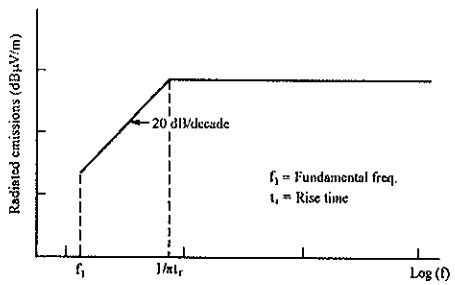
$$E = \left|E_\phi\right|_{far-field} = 1.316\times10^{-14}\left(\frac{f^2 A I}{r}\right)\sin\theta$$

DM Radiated Emissions



$$E_{max} = 2.632\times10^{-14}\left(\frac{f^2 A I}{r}\right) \text{ V/m}$$

DM Radiated Emissions Envelope



Example:

The power supply is supplying a periodic pulse current to a circuit through the V_{CC} and ground tracks. The V_{CC} and ground tracks leading to the circuit formed a loop with an area of 10 cm^2. The specifications of the periodic pulse current waveform are:

Frequency = 10 MHz
Rise time = 5ns rise time (assume fall time = rise time)
Duty cycle = 50 %
Peak current amplitude = 50 mA

(a) Plot the spectral envelope of the radiated emissions in dBμV/m from 30 MHz to 550 MHz at a distance of 3 m from the circuit.

(b) If other specifications of the current waveform remain unchanged except the rise time and fall time reduced by half, what is the impact on radiated emissions?

Solution:

(a) $I_p = 50$ mA, $\tau/T = 0.5$ and $t_r/T = 5\text{nS} / 100\text{nS} = 0.05$

The nth harmonics of the periodic pulse current is:

$$|I_n| = 50\left|\frac{\sin(0.5n\pi)}{0.5n\pi}\right|\left|\frac{\sin(0.05n\pi)}{0.05n\pi}\right| \text{ mA}$$

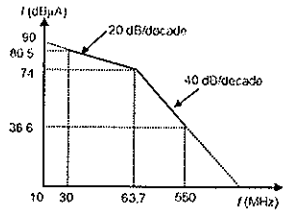
The fundamental component is:

$$|I_1| = 50 \times 0.637 \times 0.996 = 31.7 \text{ mA} = 31{,}700\ \mu\text{A}$$

$$|I_1| = 20 \log (31{,}700\ \mu\text{A}) \approx 90\ \text{dB}\mu\text{A}$$

The corner frequency = $1/\pi t_r = 63.7$ MHz

The spectral envelope of the current:



$I_{30MHz} = I_{10MHz} - 20 \log (30MHz/10MHz) = 90 - 9.5 = 80.5$ dBμA

$I_{63.7MHz} = I_{10MHz} - 20 \log (63.7MHz/10MHz) = 90 - 16 = 74$ dBμA

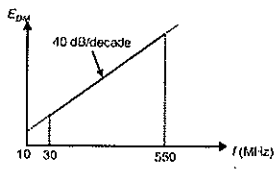
$I_{550MHz} = I_{63.7MHz} - 40 \log (550MHz/63.7MHz) = 74 - 37.4 = 36.6$ dBμA

$$E_{DM} = 2.632 \times 10^{-14} \left(\frac{f^2 A I}{r} \right) \text{ V/m}$$

Substitute $A = 10$ cm^2 and $r = 3$ m into the above expression:

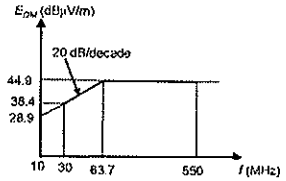
$$E_{DM} = 8.773 \times 10^{-18} f^2 I$$

For a constant current, E_{DM} is increasing at a rate of 40 dB/decade because of the f^2 term.



Taking into account of the current spectral envelope, E_{DM} will increase at a rate of 20 dB/decade till 63.7 MHz. Above 63.7 MHz, it will not increase any further.

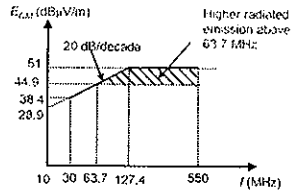
E_{DM} (fund. Freq.) = $8.773 \times 10^{-18} \times (10M)^2 \times (31.7m)$
= 27.8 μV/m or 28.9 dBμV/m



$E_{30MHz} = E_{10MHz} + 20 \log (30MHz/10MHz) = 28.9 + 9.5 = 38.4$ dBμV/m

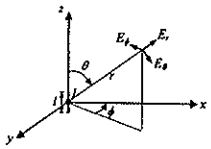
$E_{63.7MHz} = E_{10MHz} + 20 \log (63.7MHz/10MHz) = 28.9 + 16 = 44.9$ dBμV/m

(b) If the rise and fall times are halved, the corner frequency will be doubled from 63.7 MHz to 127.4 MHz. The new radiated emissions spectral envelope will be:



$$E_{127.4MHz} = E_{10MHz} + 20 \log (127.4MHz/10MHz)$$
$$= 28.9 + 22.1 = 51\ dB\mu V/m$$

Radiated Electric Field From a Wire



$$E_r = \frac{2Iz_0\beta_0^2}{4\pi}\cos\theta\left(\frac{1}{\beta_0^2 r^2} - j\frac{1}{\beta_0^3 r^3}\right)e^{-j\beta_0 r}$$

$$E_\theta = \frac{Iz_0\beta_0^2}{4\pi}\sin\theta\left(j\frac{1}{\beta_0 r} + \frac{1}{\beta_0^2 r^2} - j\frac{1}{\beta_0^3 r^3}\right)e^{-j\beta_0 r}$$

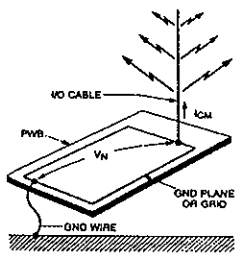
$$E_\phi = 0$$

$$E_r = 0 \quad \because \frac{1}{\beta^2_{0}r^2} \text{ and } \frac{1}{\beta^3_{0}r^3} \to 0$$

$$E_\theta = \frac{Iz_0\beta_0^2}{4\pi}\sin\theta\left(j\frac{1}{\beta_0 r}\right)e^{-j\beta_0 r} \quad \because \frac{1}{\beta^2_{0}r^2} \text{ and } \frac{1}{\beta^3_{0}r^3} \to 0$$

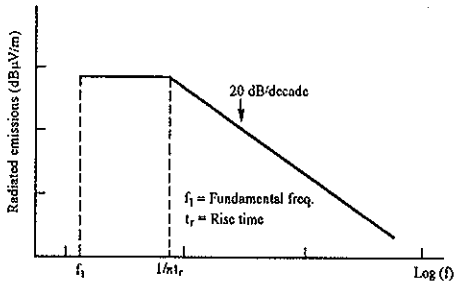
$$E = |E_\theta|_{far\text{-}field} = 6.283\times10^{-7}\left(\frac{fIl}{r}\right)\sin\theta$$

Common-mode radiated EMI



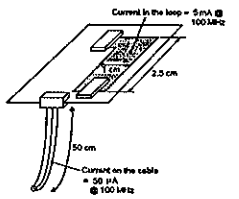
$$E_{max} = 1.26\times10^{-6}\left(\frac{fIl}{r}\right) \text{ V/m}$$

CM radiated emission envelope



Example:

A PCB with an attached I/O cable is shown below. With the given spectral current amplitudes at 100 MHz for the circuit loop and the I/O cable, will the whole assembly pass the FCC part 15 class B radiated emission limit at 100 MHz?



FCC part 15 class B limits for digital devices

Frequency (MHz)	Limits at 3 m (dBμV/m)
30-88	40
88-216	43.5
216-960	46
>960	54

Solution:

The circuit loop generates DM radiation:

$$E_{DM} = 2.632 \times 10^{-16} \left(\frac{f^2 A I}{r} \right) \text{ V/m}$$

$A \approx 2.5$ cm $\times$ 1 cm $= 2.5$ cm^2, $f = 100$ MHz, $I = 5$ mA, and $r = 3$ m (FCC class B test distance)

The calculated DM radiation from the circuit loop is:

$$E_{DM} = 109.7\ \mu\text{V/m or } 20 \log (109.7\ \mu\text{V/m}) = 40.8\ \text{dB}\mu\text{V/m}$$

The I/O cable generates CM radiation:

$$E_{CM} = 1.26 \times 10^{-6} \left(\frac{f l I}{r} \right) \text{ V/m}$$

$l = 50$ cm, $f = 100$ MHz, $I = 50$ μA and $r = 3$ m (FCC class B test distance)

The calculated CM radiation from the I/O cable is:

E_{CM} = 1050 μV/m or 20 log (1050 μV/m) = 60.4 dBμV/m

The calculated E_{DM} and E_{CM} at 100 MHz show that CM radiation is the dominant mode of radiation (about 20 dB higher). Hence, the overall resultant radiation is decided by CM radiation.

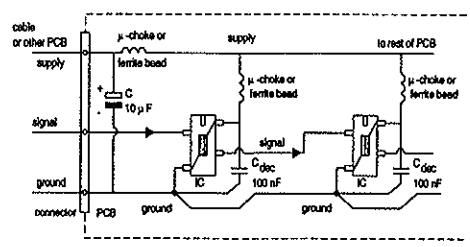
The resultant radiation @ 100 MHz is 60.4 dBμV/m, which has exceeded FCC class B limit (43.5 dBμV/m @ 100 MHz) by 16.9 dB.

Therefore, the PCB with the attached I/O cable is going to fail the FCC class B radiated EMI test.

General Strategy to Minimize Radiated Emissions

- To minimize DM radiated EMI → to reduce the loop areas that contain signals of high spectral contents, such as switching currents from dc power supply and high frequency clock signal
- To minimize CM radiation → to reduce ground bounces → to reduce ground inductance
- Proper PCB layout becomes a crucial issue

Power Supply Decoupling



Value of Local Decoupling Cap

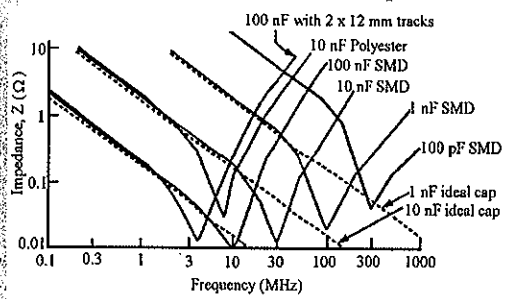
$$C = I\left(\frac{\Delta V}{\Delta t}\right)$$

I is the IC's transient current demand from its power supply

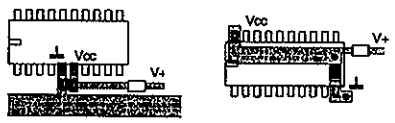
Δt is the time that the transient current lasts

ΔV is the allowable tolerance on the IC's power supply voltage

Self-resonance Limitations of Capacitors



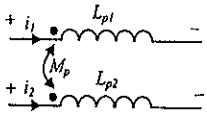
Placement of Local Decoupling Cap



LEGEND

- via in GND or supply
- Decoupling capacitor 10 - 100 nF
- Ferrite bead inductor 50 - >1000 ohm
- + / Vcc Local power supply of IC
- V+ Common power supply on PCB
- Ground (GND)

Trace Inductance of a Signal Path



$$V_1 = L_{p1}\frac{di_1}{dt} + M_p\frac{di_2}{dt}$$

$$V_2 = M_p\frac{di_1}{dt} + L_{p2}\frac{di_2}{dt}$$

If $i_1 = i$ and $i_2 = -i$, then

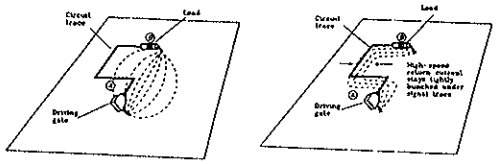
$$V_1 = (L_{p1} - M_p)\frac{di}{dt}$$

$$V_2 = -(L_{p2} - M_p)\frac{di}{dt}$$

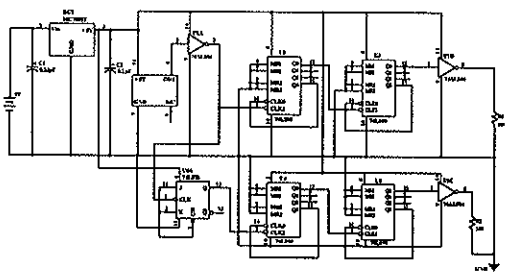
Current Return Path of a Signal Trace

Low frequency signal

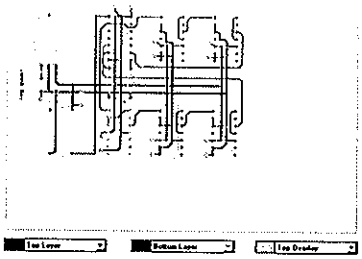
High frequency signal



Digital Circuit for Case Study



PCB Layout A



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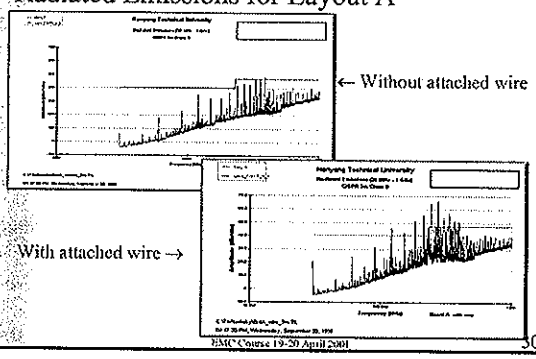
Radiated Emissions for Layout A



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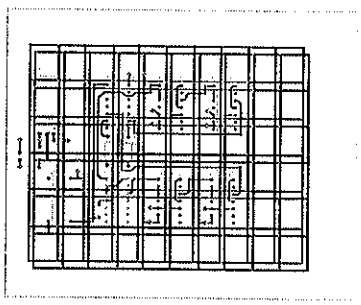
PCB Layout B



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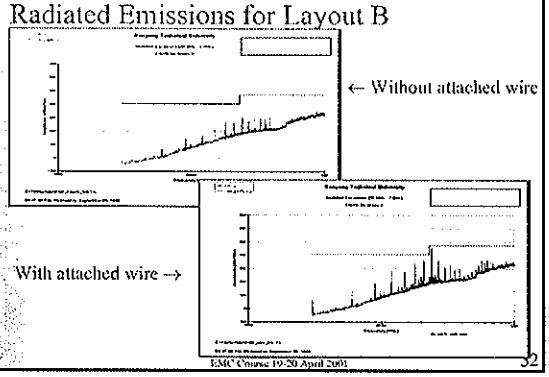
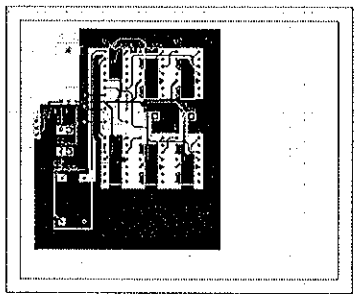
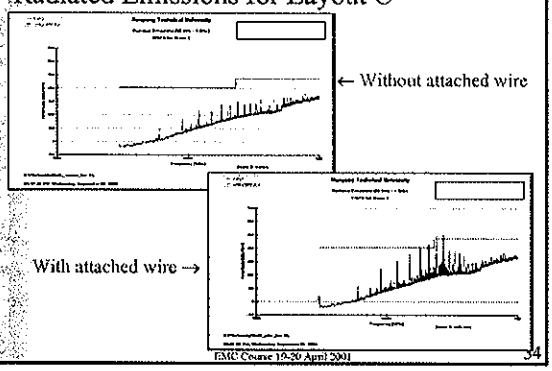
Radiated Emissions for Layout B



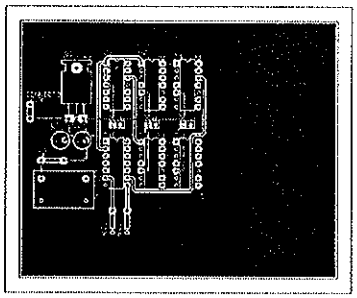
PCB Layout C



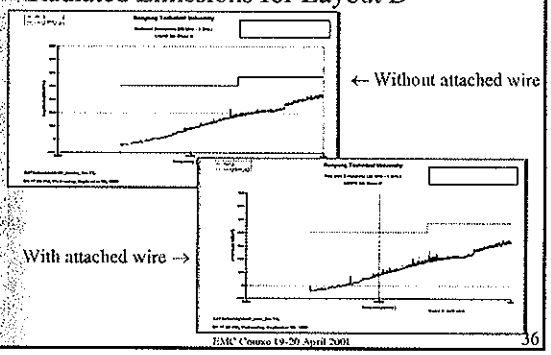
Radiated Emissions for Layout C



PCB Layout D



Radiated Emissions for Layout D



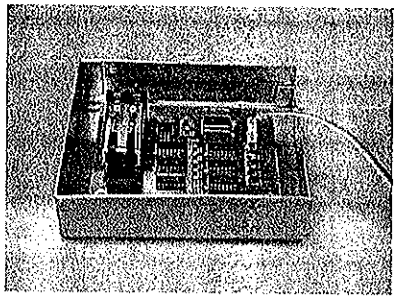
← Without attached wire

With attached wire →

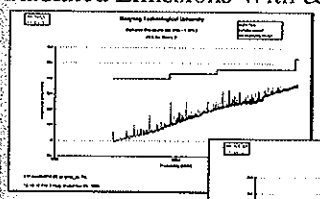
Controlling CM Radiation from Cables

- Minimize the CM radiation source voltage → reduce ground bounces → proper PCB layout to reduce the ground inductance
- Provide a large CM impedance to reduce CM noise current → add ferrite sleeve in the CM path
- Bypass the CM noise current to ground → add capacitor to shunt high frequency CM noise current to ground

Case Study for CM Emissions from Cable

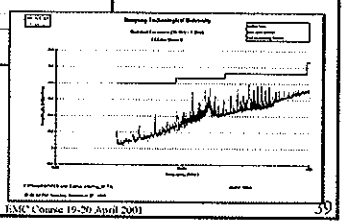


Radiated Emissions With & Without Cable

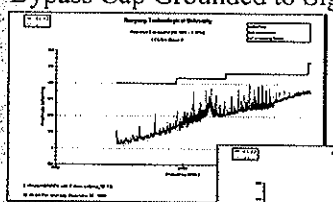


← Without cable

With cable →

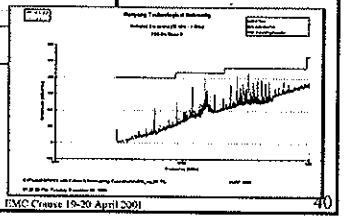


Bypass Cap Grounded to Signal Ground

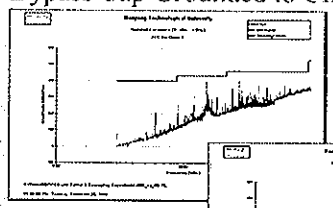


← Without bypass cap

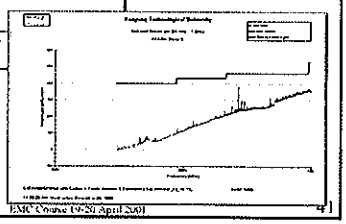
With bypass cap grounded to signal ground →



Bypass Cap Grounded to Chassis Ground



← With bypass cap grounded to signal ground



With bypass cap grounded to chassis ground →

EMC Test Approach
&
EMC Test Facilities

Chow Wee Sing

CET TECHNOLOGIES PTE LTD

Agenda

- Why EMC Testing?
- What is Electromagnetic Environment?
- Emission/Susceptibility Test Objectives
- Type of Test
- EMC Test Standards
- Diagnostic versus Compliance Test
- EMC Test Methodology
- EMC Test Environment and Equipment

Why EMC Testing??

Rationales for EMC Testing (Policy)

- ***EMC Test as a regulatory control***
  - e.g. Federal Communications Commission (FCC)
    - *This equipment has been tested by XXX, and found to comply with the limits for the Class B digital device, persuant to Part 15 of the FCC Rules. This limits are designed to provide reasonable protection against harmful interference in a residential installation....However, there is no guarantee that interference will not occur in a particular installation...*
  - e.g. CE Compliance Statement
    - *This product was tested by XXX and found to comply with all the requirements of the EMC Directive 89/336/EEC as amended..*

Rationales for EMC Testing (Policy)

- ***EMC Test as contractual requirements***
  - e.g. The Contractor is required to conduct TYPE tests... *Tests to be conducted shall include but not limit to satisfying the standards as follows:*
    - *EN 61000-4-2/3/4/5/6/8/9/10/11/12/13/14/16/17/28....*
  - *Note : The product committee (or **users and manufacturers of equipment**) remain responsible for appropriate choice of the test and the severity level to be applied to their equipment. (ref: Scope of EN 61000-4 standards)*

Rationales for EMC Test (Engineering)

- *Simulating the **effect of potential electromagnetic interference phenomena** on a newly installed system.*
- *Preventive measures to **minimize System Performance Degradation** due to potential environmental electromagnetic disturbances.*

Electromagnetic Environment

- ***Continuous Interference*** : Interference effect is observed continuously when noise source is *On or Active*, and disappears when noise source is *Off*.
- ***Intermittent Interference*** : Interference effects occurs sporadically at varying time intervals,which can vary from seconds to days (or weeks) *between Occurrences*.

Electromagnetic Environment

- ***Conducted/Radiated (continuous)*** electromagnetic emissions are often characterized by *Amplitude versus Frequency Spectra.*
  - **e.g. RF sources, non-intentional radiators.**
- ***Transient*** electromagnetic noise are characterized by *time-domain pulses*, either unipolar and/or oscillatory.
  - **e.g. Power-line related disturbances.**

Emission/Susceptibility Testing Objectives

- ***Emission specification*** ***(low emission level)*** serves to limit the upper lever of non-intentional emissions from EUT in the *intended* operating environment
- ***Susceptibility specification*** ***(high immunity level)*** assures that the EUT will perform in the presence of *intended* external electromagnetic emissions in its operating environment (changing electromagnetic environment)

Type of EMC Test

- ***Conducted Emission/Susceptibility (CE/CS)***
  - Low frequency phenomena (e.g. harmonics, voltage fluctuation, dip, unbalance, induced LF voltages)
  - High frequency phenomena (e.g. induced CW voltage or currents, undirectional/oscillatory transients)
- ***Radiated Emission/Susceptibility (RE/RS)***
  - LF magnetic & electric fields
  - HF magnetic & electric fields and electromagnetic fields (Continuous/transient)

EMC Test Standards

- ***Component and Equipment-level Tests***

	Standards	*Subject*
Military	MIL-STD-461/462	*Equipment / sub-system*
	MIL-STD-449	*Transmitter / Receiver*
Commercial	EN 55022	*Conducted / Radiated emissions*
	EN 61000-4-2	*Electrostatic Discharge*
	EN 61000-4-3	*Radiated Immunity*
	EN 61000-4-4	*Electrical Fast Transient Immunity*
	EN 61000-4-5	*Surge Immunity*

Diagnostic vs Compliance Test

- ***Diagnostic testing*** is used during product development cycle to trouble-shoot potential EMI problem areas and pre-qualify the product

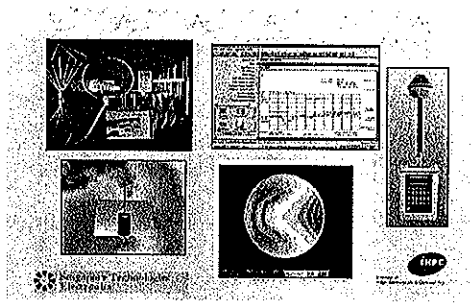


- ***Compliance or qualification testing*** is the final test that must be passed prior to
  - certification (as per regulatory requirements), or
  - final acceptance (as per contractual agreement)

EMC Test Methodology

- *Identify & confirm on the **EMC Test requirements** (as per regulatory or contractual requirement)*
- *Develop an **EMC Test Plan** and suitable **Procedure***
- *Prepare for proper **test setup** with supporting equipment, if any.*
- *Execute the **EMC Test methods** in according to the test plan and procedure.*
- ***Analyze the results** and recommendations for improvement, if necessary.*

EMI Test Environment & Equipment

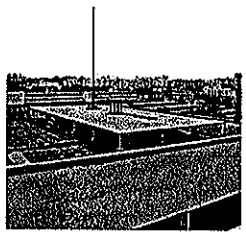


EMI Test Environment & Equipment Requirements

- Used to determine and verify compliance with the applicable emission and susceptibility requirements of the relevant EMC Test standards.
- Measurement tolerances are used to maintain reasonable controls for obtaining consistent measurements. (e.g MIL-STD-461E)
  - Distance : +/-5%
  - frequency : +/-2%
  - Amplitude, measurement system : +/- 3dB

Open Area Test Site

- Measurement of ***Radiated Emissions***
  - Antenna mast /receiving antenna
  - Calibrated EMI receiver
  - Maximize the E-field strength measured at a certain antenna height and EUT's azimuth.

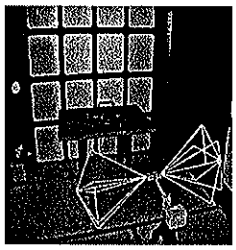


Open Area Test Site

- Primary sources of errors :
  - site imperfections
  - inaccuracies in antenna characterization
  - direct coupling of EM energy between EUT and transmit/receive antennas
  - measurement & calibration uncertainties of T&M equipment
  - No isolation from external electromagnetic environment
- Ideal conditions
  - Infinite free space
  - Perfectly conducting ground plane
  - No background noise
  - No mutual coupling

Anechoic Chamber

- ***Radiated /Conducted Emissions and Susceptibility test***
  - indoor facility with high isolation of 100dB from external electromagnetic environment.
  - Low level signals measurement in RE test
  - High E-Field generation in RS test



Anechoic Chamber

- Particular useful in the frequency range of 30 MHz to 10GHz for both RE and RS measurement
- Used for compliance testing of military standards MIL-STD 461/462 and commercial standards FCC, VDE etc
- Amount of test space is limited by the size of "quiet zone", which in turn is limited by the chamber size.
- Uncertainties in measurement due to inability of this chamber to provide a truly free-space environment for RS and RE tests.

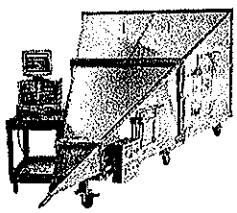
Anechoic Chamber

- Sources of uncertainties in measurement
  - Quality of the chamber (ie. level of reflection from the walls of the anechoic chamber)
  - exactness of the relationship between the electromagnetic fields surrounding the antenna inside the chamber and the voltage or power measured at the receiver point or transmitter antenna. (due to uncertainties in cable losses; antenna factor; and distance between EUT & antenna)

A particular standard NIST laboratory setup, worst-case overall uncertainty in field strength measured is estimated to be +/- 1.0 dB

Giga-Hertz TEM Cell

- 50 ohm tapered rectangular coaxial transmission with septum
- Geometry does not permit standing waves produced by EM fields generated within to be sustained.
- Field strength is a function of input power, as well as location along the longitudinal axis

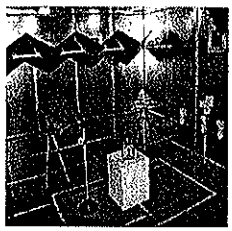


GTEM Cell

- Eliminates most of the reflections and resonances inherent in the other test facilities.
- Associated program needed for interpretation of measurement results into radiated emissions at distances of 3m or 10m from EUT
- Measurement can be done in laboratory, and for quality control purposes in production floor.
- As compared to anechoic chamber, lesser RF power is needed to generate the same level of E-field in RS test. This implies a more cost-effective approach in susceptibility test for small EUT.

Reverberation Chamber

- Based on multi-mode resonance mixing using rotating stirrer inside a shielded room.
- Uniform field established as a result of the presence of several modes sufficiently closed to one another.
- Desired field level is generated through an amplified signal source



Reverberation Chamber

- Provides a good isolation from the external electromagnetic environment
- Capable of yielding efficient field conversion, thus making it possible to conduct RS testing at high field strength such as 200V/m
- Alternate test site for Commercial standards IEC61000-4-3/21, RTCA DO-160D, EUROCAE WG 14/33, SAE J1113/27, GM-9120P and military MIL-STD-461E
- Data intensive and statistical model

Reverberation Chamber

- Polarization properties are not preserved.
- Proper sampling techniques reduce measurement uncertainties.
- Results are insensitive to EUT placement inside the test volume.
- Results are independent of EUT radiation pattern
- Reverberation Chamber capture total radiated power.
- Acceptance of reverberation chamber as valid EMC test facility is growing.

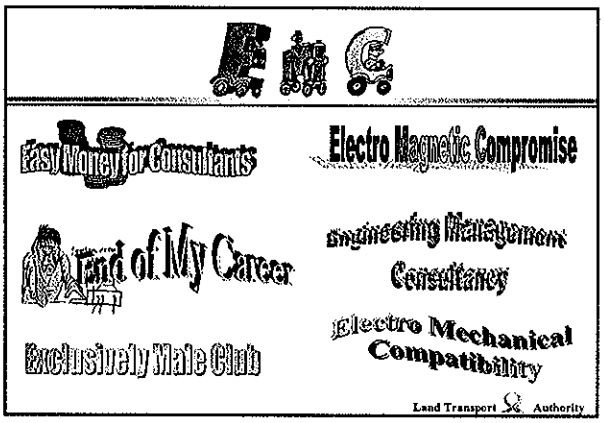
EMC MANAGEMENT FOR TRANSIT AND TRAFFIC PROJECTS

Sam Chan
Systems Integration Department
Projects and Engineering Division
20th April, 2001

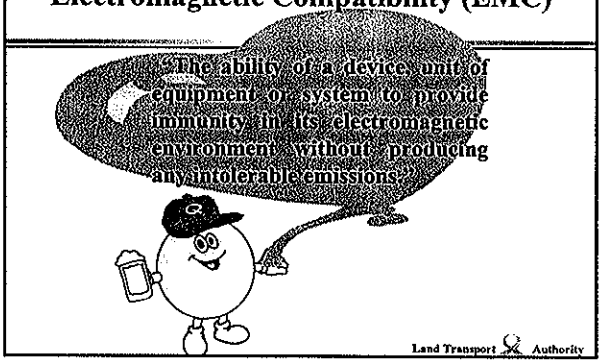
Land Transport Authority

Overview

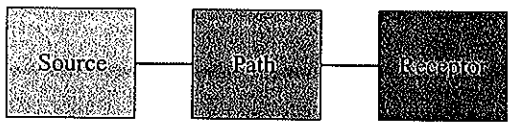
- Introduction
- Transit and Traffic EMC Standards
- Railway EMC
- EMC Management
- Implementation Problems
- The Way Forward



Electromagnetic Compatibility (EMC)



Basic Concepts



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Coupling Paths

- Conduction
- Radiation
- Inductive Coupling
- Capacitive Coupling

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Corrective Measures

Cable Separation

Prevent Noise Coupling

Filtering

Reduce Conducted Noise

Transient Suppression

Remove High Transient energy

Shielding

Confine Electromagnetic Energy

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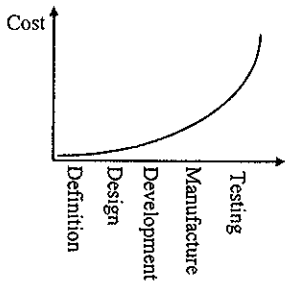
Cost Of EMC



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EMC Knowledge

- Basic Electromagnetism
- Harmonic Theory
- Telecommunication
- Microwave
- Antenna Design
- Field Analysis
- Management

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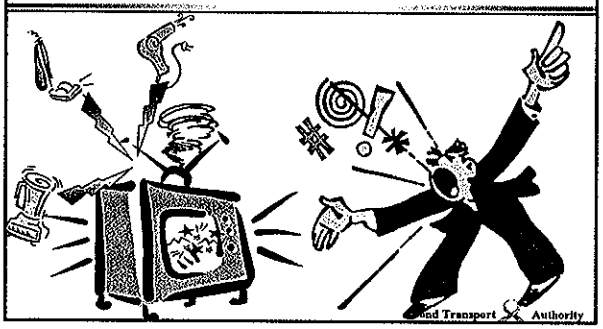
EMI Examples



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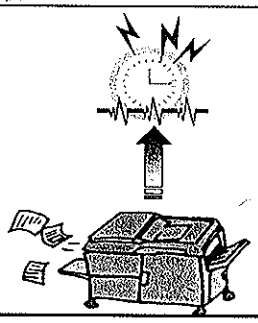
EMI Examples



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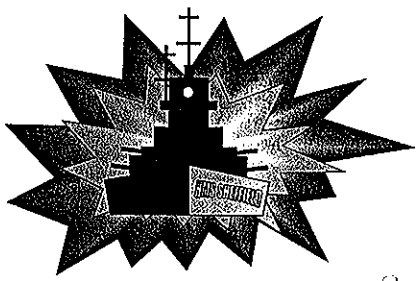
EMI Examples



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European EMC Directive

- EMC Directive 89/336/EEC becomes mandatory in 1996
- Applies to most electrical products for sale in the EU
- A measure to remove technical barriers to trade in the EU
- Controls pollution of the electromagnetic spectrum

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The Essential Requirements

Apparatus shall be so constructed that:

a) The electromagnetic disturbance it generates does not exceed a level allowing radio and telecommunications equipment and other apparatus to operate as intended.

b) The apparatus has an adequate level of intrinsic immunity of electromagnetic disturbance to enable it to operate as intended.

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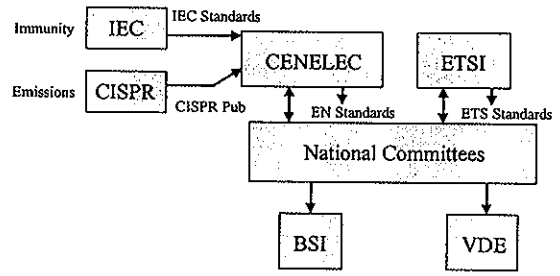
Standard Making Bodies



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Euro-Norm Standards (EN)

- Generic & Product Specific Standards
- Emission & Immunity
- Basic Standards

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Generic EN Standards

Residential, Commercial and Light Industry

EN 50081 - 1 : Generic Emission Standard

EN 50082 - 1 : Generic Immunity Standard

Industrial

EN 50081 - 2 : Generic Emission Standard

EN 50082 - 2 : Generic Immunity Standard

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Product Specific Standards

Emission of Electrical Lighting

EN 55015

Immunity of Sound and Television Broadcast Receivers

EN 55020

Information Technology Equipment

EN 55022

Disturbance in Supply Systems

EN 60555

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Railway Specific EMC Standards

EN 50121 - 1	Introduction
- 2	Outside World
- 3 - 1	Complete Railway Vehicle
- 3 - 2	Apparatus on Railway Vehicle
- 4	Signalling & Comms
- 5	Fixed Installations

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Vehicle EMC

Testing on both Vehicle and Electronic Sub-assembly

- Radiated Broadband Emission
- Radiated narrowband Emission
- Radiated Immunity

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Vehicle Specific EMC Standards

a) Radiated Broadband Emission
   . similar to 72/245/EEC
   . intended for spark ignition system from 30MHz - 1 GHz

b) Radiated Narrow Band Emission
   . CISPR25

c) Radiated Immunity
   . similar to ISO/DIS 11451-2
   . using anechoic chamber at 30V/m

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IEC 1000-X Standards

Number	Description	Contents
1000 - 1	General Considerations	Introductory, Fundamental
1000 - 2	Environments	Description, Classes & Levels
1000 - 3	Limits	EMC Limits
1000 - 4	Test & Measurement Techniques	Procedures & Methods
1000 - 5	Installation & Mitigation Guidelines	

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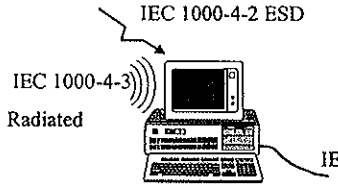
IEC 1000 - 4



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Radiated EMC Measurement

- Loop Antenna - 9kHz to 30MHz
- Bi-conical Antenna - 30MHz to 300MHz
- Log - Period Antenna - 300MHz to 1GHz
- Horn Antenna - 1 GHz to 10GHz

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Routes To Compliance

- Self certification to standards
- Technical Construction File (TCF)
- EC type examination for radio equipment

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Technical Construction File

- No applicable harmonised standard
- Harmonised standards applied only in part
- Physical properties of installation

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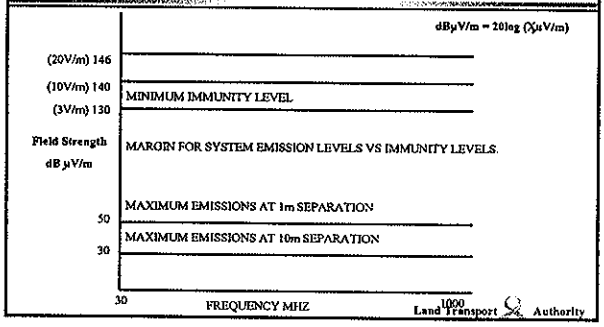
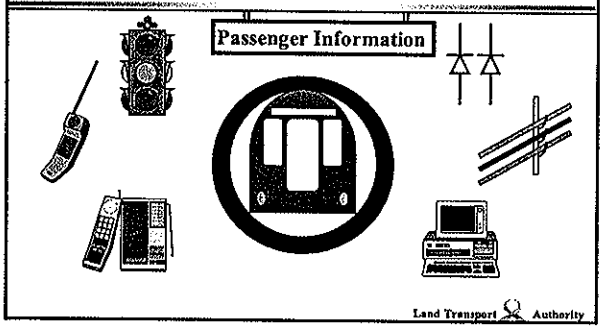
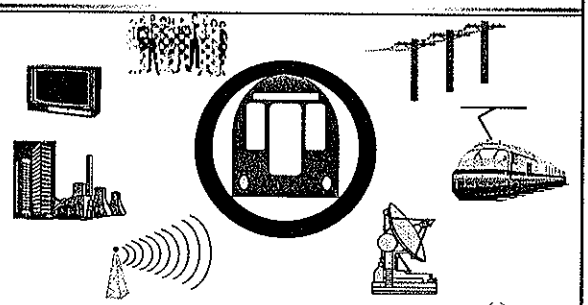
Immunity VS Emission Levels



Internal Effects



External Effects



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Frequency Table For Typical Railway Systems

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Compatibility with Airport System

Frequency	Description
KHz range	Track Circuits/ATO Loop Other signalling frequencies Non-Directional Beacon (NDB)
MHz range	HF Long Range Voice, Middle Marker Existing Train Radio, ILS Localiser, Doppler VHF Omnidirectional Air Traffic Control, Radio Directional Finder, Company-to-Pilot, Data Link, ILS Glide Path Train Radio (Upgrade) UHF & radio system
GHz range	Distance Measuring Equipment (DME), Long Range primary/secondary Radar, Approach primary/secondary Radar, Meteorological Radar Airport Surface Detection Equipment

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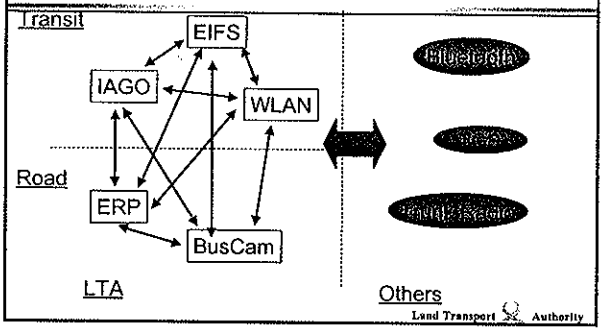
ISM BAND COMPATIBILITY



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Key Areas Of Interest

- Low frequency signalling compatibility with Train/Power
- Operation of handheld portables near equipment
- DC magnetic field on CRT monitors
- Separation between high current power and low current signalling cables
- Equipment operating above 1 GHz
- Large System Testing/ 'In-situ' Testing
- Compatibility with Mindef
- Compatibility with Airport

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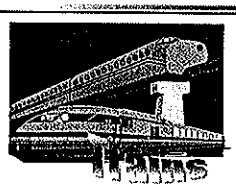
EMC For Track Circuits







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Safety Implication



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Induced Longitudinal Voltage & Transverse Voltage :

CCITT Recommendation:

- Longitudinal Voltage to Earth - Normal Condition — 60V
- Longitudinal Voltage to Earth - Fault Condition — 430V
- Psophometrically weighted Transverse Voltage (Noise) — 1mV

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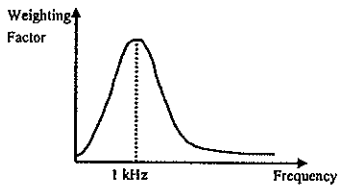
Psophometric Noise



$$Vpso = \sqrt{\sum_i (V_i f_i)^2}$$ **Root-mean-square**

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Cable Separation

- Source current magnitude
- Length of parallel exposure
- Separation between cables
- Overall screening factor
- Earthing arrangement & earth resistivity
- Frequencies of concern

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EMC Strategy

- Project inception to decommissioning.
  - cradle to death
  - lust to dust
- Engineering principles, not just rules of thumb.
- More expensive as the system evolves.
- More resources on design, less on testing.
- Immunity test failure can be very expensive.
- EMC management and co-ordination is the key.

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Multi-Contract VS Turnkey Contract

- EMC for Multi-Contracts
  - Multi-Contract Nature
  - Overall System Compatibility by LTA
  - Extensive Effort on both Intra-System & Inter-System EMC
- EMC for Turnkey Contract
  - One Turn-Key Contract
  - Overall System Responsibility is managed by the Turn-Key Contractor
  - EMC Focus on Railway with External Environment

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EMC Activities

- Specification Stage
  - Identify threats
  - Research Standards
  - Specify Requirements
- Tender Stage
  - Assess EMC performance of Tenderers
  - Amend Requirements where necessary
- Design & Manufacturing Stage
  - Monitor progress of Contractors
  - Review EMC Submissions/Attend meetings
- Testing Stage
  - Accept Test Specification
  - Witness Testing

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Preliminary Design Stage

- EMC Management Plan
- EMC Philosophy & Approach
- Pre-installation EMC Survey Specification & Report
- Initial EMI Hazard Analysis
- Complete Frequency Plan for all sub-systems
- EMC Programme

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Pre-Final Design Stage

- EMC Specification for each sub-system
- EMC Impact Analysis Report
- Induced Voltage Study for all Cables
- EMC Cabling Constraints
- Preliminary EMC tests on prototypes
- Antenna Coverage Diagrams for Comms System
- DC Magnetic Field Study on all CRT monitors
- EMC Summary Report for Pre-Final Stage

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Final Design Stage

- Final EMI Hazard Analysis Report
- EMC Test Plan & Specification for each sub-system
- EMC Integrated Testing & Commissioning Plan
- EMC Compliance Matrix
- Complete Signalling/Communications/Rolling Stock Compatibility Specification
- EMC Summary Report for Pre-Final Stage

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Manufacturing/Type Testing/ Factory Testing Stage

- EMC Type Test Reports
- EMC Factory Acceptance Test Reports
  (e.g. Harmonic measurements during combined system testing)

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Installation Stage



- Report on Site Constraints & Associated Corrective Measures

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Integrated Testing & Commissioning Stage

- Post Installation EMC site survey report
- Integrated Test Reports (including whole system emission tests and all low frequency compatibility tests)
- Technical Construction File (TCF) for equipment which cannot be tested
- Overall System EMC Summary Report

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Maintenance

- EMC Documentation for any modifications
- Re-test if necessary



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Problems

- Performance based Contracts
  - low frequency EMC/Microwave frequency
  - DC magnetic field
- Off-the-shelf/existing equipment
- Close loop feedback to the design process
- Contractors' priority & attitude
- EMC by testing only
- Cable Separation
- Higher Immunity Limit above normal industrial standard
- Integration

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Interesting External Problems

- Railway power generating station affecting teaching equipment of nearby school for deaf
- Inductive coupling on automated guided robots of printing factory
- Orientation of Dolphins in an aquarium above the railway
- Health Hazards on residents nearby a traction substation
- Compatibility of Contactless-card readers with handphones
- Protection for Heart Pace Makers
- Compatibility with Instrument Landing System

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The Way Forward

- EMC is important to safe & reliable railway operation
- Whole-System & Whole-life consideration is required
- Special attention required for railway specific problems
- Established framework and process to manage further problems
- Continued update on latest development

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