Wired and wireless networks

PATO EMC

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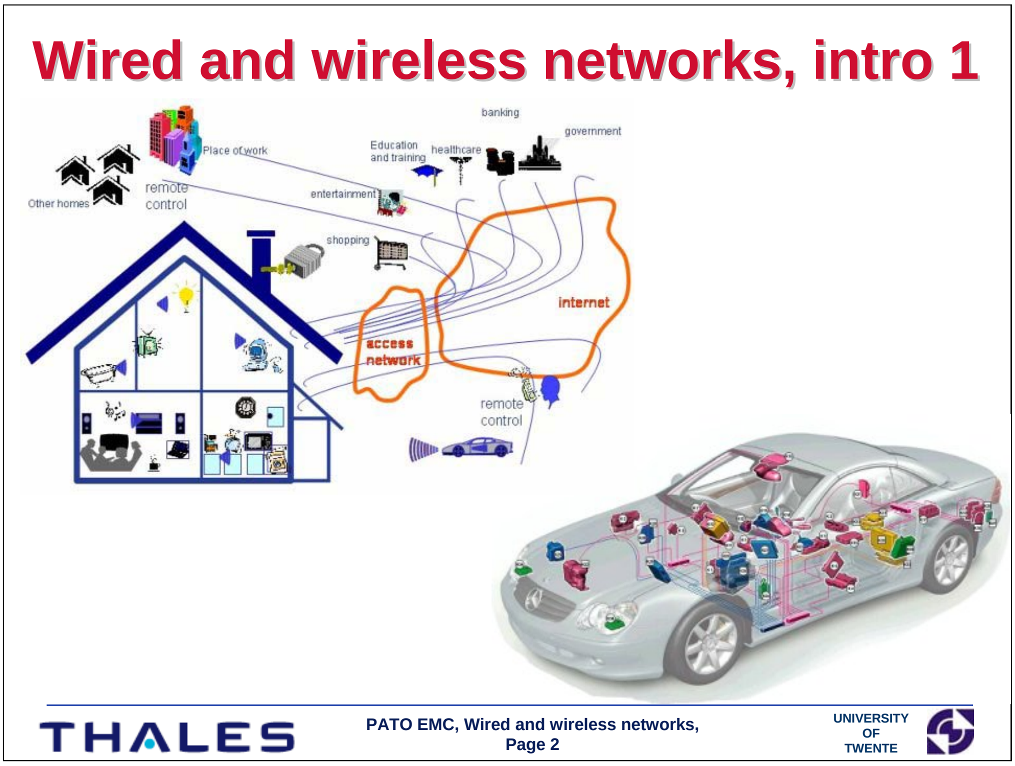
We will discuss typical issues of wired and wireless networks, with an impact on EMI.

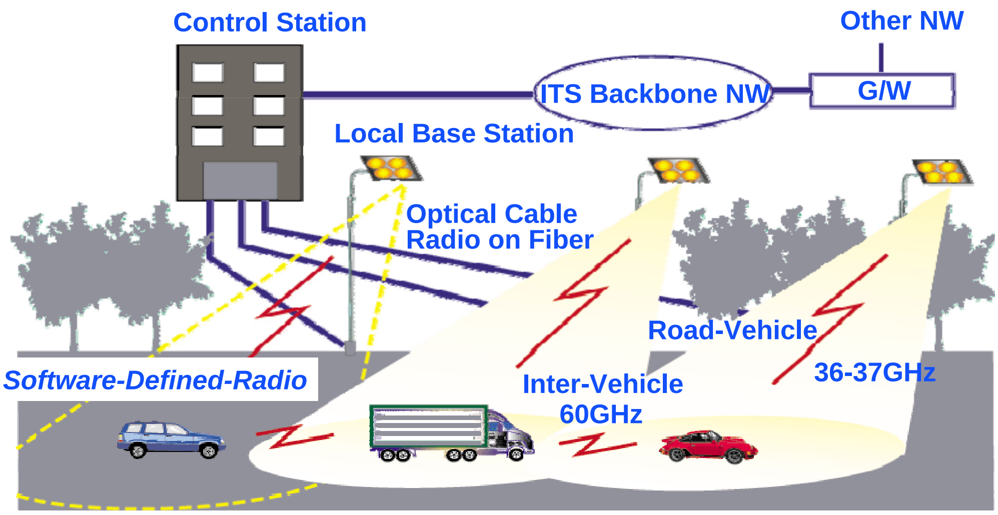
We will discuss advantages and disadvantages of balanced and unbalanced networks, again with an emphasis on EMI. We will discuss briefly high-speed networks and basic issues of wireless networks. Then we will discuss EMI mitigation techniques and implementations.



Wired and wireless networks are become a standard item in our environment.

Networks, introduction 2

Integrated Traffic Communication System



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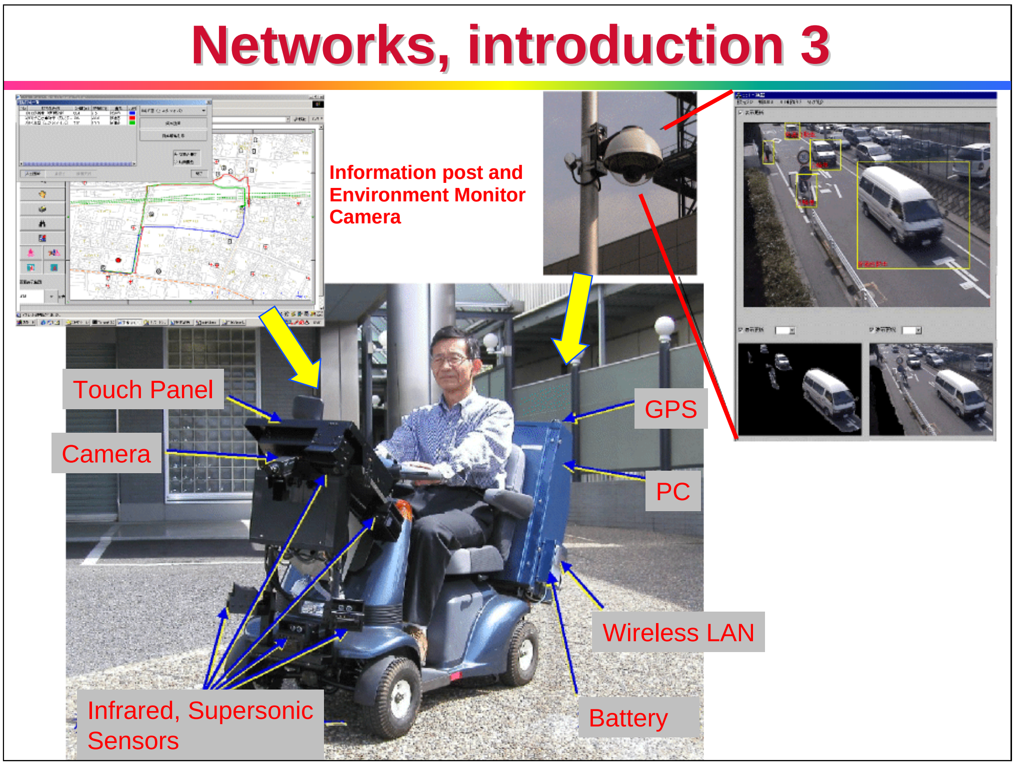
In Intelligent Transport Systems many different types of communication systems are being used for safety and comfort.



And even wheelchairs, with GPS, Wireless LAN, Sensor network, PC, etc. etc..
But the wheelchair still has to operate without degradation of performance in its environment. The article shown below (IEEE EMC Society Newsletter, 2004) describes the EMI problem of a wheelchair being susceptible to a 1.8 GHz GSM repeater in a metro-station. The wheelchair fulfils the legislative requirements (CE mark) by fulfilling the applicable standards. However: the EMC Directive states that fulfilling the requirements of the standards is a way to fulfil the essential requirements of the EMC Directive. The manufacturer should know that 1.8 GHz repeaters can be used, and he should have taken this into account. The manufacturer was sentenced.

The Jammed Wheelchair: A Case Study of EMC and Functional Safety

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Abstract: The assessment of the influence of electromagnetic phenomena on the functional safety of electric equipment can be improved. The product standards for electric equipment with safety relevant functions still focus on the functional behaviour. The EMC requirements are quite often composed by following the same approach as for the Generic Standards for the EMC Directive in which only two environments are taken into account. In order to explain this and to show a better approach, a case study has been carried out. The essence of this case is an accident with an electric wheelchair where the culprit was a GSM-phone booster. Point of interest is that the wheel-chair did meet the relevant product standard for electric wheel-chairs. The shortcomings of this standard with respect to EMC have been established. In addition, it is shown that an assessment should start with an inventory of the environments in which the product might be operated. This improved assessment is in line with the relatively new IEC Technical Specification 61000-1-2: 'Methodology for the achievement of functional safety of electrical and electronic equipment'.

I. Introduction

Figure 1. An ordinary street with cars and an electric wheelchair: one environment – different EMC requirements.

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Rolstoelen op hol door gsm's

Van onze Haagse redactie 23/2/98
WOERDEN, maandag

Mobiele telefoons kunnen een elektrische rolstoel op hol doen laten slaan. Door de straling die vrijkomt bij het gebruik van de zaktelefoon kan de afstandsbediening van de rolstoel in werking treden.

Dat zegt de belangenorganisatie voor mindervaliden, KBOH in Woerden. Volgens deze instelling zijn door het gebruik van gsm-toestellen de laatste twee jaar diverse klachten binnengekomen van rolstoelers die op hol zijn geslagen.

De organisatie spreekt van levensgevaarlijke toestanden. Verschillende keren zijn rolstoelers al als gevolg van de mobiele telefoon in vijvers en sloten terecht gekomen.

De KBOH raadt lichamelijk gehandicapten dan ook aan hun klachten te deponeren bij de overheid.

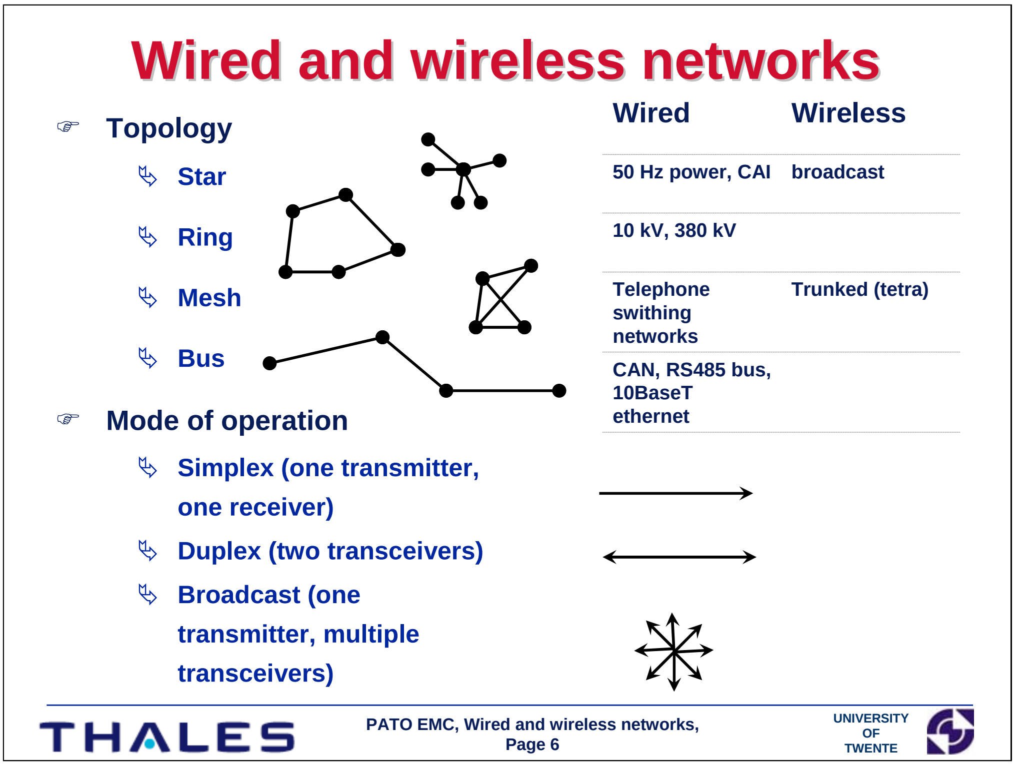
Het Staatstoezicht op de Volksgezondheid raadt op invaliden op zijn beurt aan hun rolstoel te laten onderzoeken op de gevoeligheid van elektromagnetische straling. Vaak blijkt namelijk dat de elektronica van de rolstoel niet goed is beschermd, waardoor mobiele telefoons deze ongewild in werking kunnen zetten.

Volgens de KBOH betreft het met name oudere rolstoelen, waaraan door ondeskundigen veranderingen zijn aangebracht.

Om dit soort problemen te voorkomen dient vooral kritisch te worden gekeken naar de isolatie van het elektrische circuit van de rolstoel.

Maybe you remember the problem of wheelchairs being remotely operated by a 27 MHz transmitter.

Mr. Bean is also very powerful….



Networks are everywhere in our high-tech society.

In general, the topology is eithe star, ring, mesh or bus. Examples are:

- •The 50 Hz mains supply
- •The PSTN: public switched telephone network
- •The central antenna installation (CAI)
- •Datacommunication networks in and between buildings, such as ethernet
- •Datacommunication networks in and between cabinets (RS485, CAN-bus etc.)

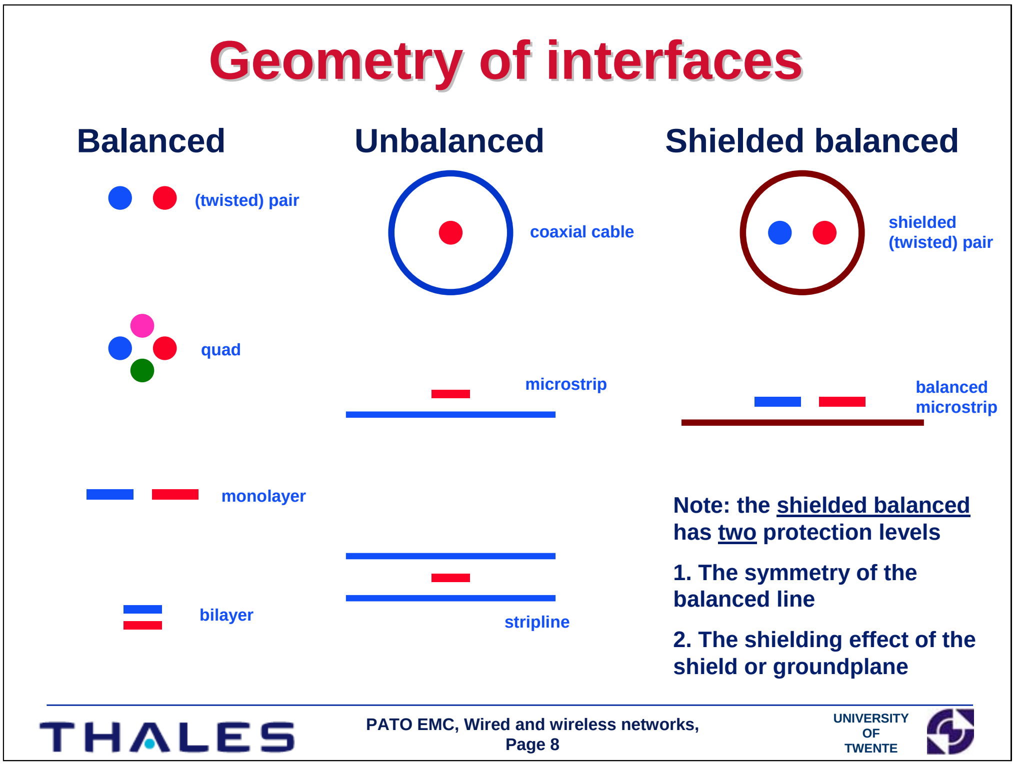
Wired (copper) networks

- **Trend: more services over the same cable:**
  - **Datacommunication over mains supply network (PLC: power line communication)**
  - **Digital communication over PSTN (ADSL: asynchronous digital subscriber line)**
  - **Data communication over CAI**
- **Trend: high-speed networks: equalizers, compensation, unwanted emission**
- **Many EMI issues**
- **Now: wired, then wireless….**

Daarnaast worden meer diensten over dezelfde kabels geleid, bijvoorbeeld

- Datacommunicatie over voedingsnet (PLC: power line communication)
- Digitale communicatie over PSTN (ISDN: integrated services digital network, ADSL: asynchronous digital subscriber line)
- Data communicatie over CAI

De gedachte om data signalen over reeds aangelegde verbindingen te leggen lijkt heel slim: er ligt immers al een kabel in de grond waarvan maar een beperkt deel van de capaciteit wordt gebruikt. Door andere signalen erover te sturen wordt de capaciteit vergroot, waarbij die kabel een extra melkkoe wordt. Jammer genoeg gaat dit gepaard met vele EMI problemen, omdat die netwerken niet waren bedoeld voor deze communicatie.



We kunnen onderscheid maken in

- •Gebalanceerde verbindingen
- •Ongebalanceerde verbindingen

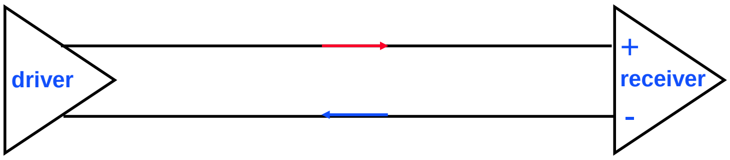
Daarnaast zijn er nog diverse samenstellingen, waaronder afgeschermde gebalanceerde verbindingen.

We zullen gebalanceerde en ongebalanceerde verbindingen uitgebreid bespreken, aangezien beide worden toegepast in diverse soorten netwerken.

Beide typen hebben voor- en nadelen.

Balanced, 1

- Applications
  - Audio input and output: microphone resp. speakers
  - Data bus:
    - CAN bus in automotive world
    - RS 485 bus in and between cabinets
  - Local Area Network (LAN):
    - Unshielded twisted pair (UTP), for classic LANs
    - Quad (2-UTPs) for high-speed ethernet
- UTP, RS485, CAN bus etc.:



- Ground connection not needed

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Voorbeeld 1: Ethernet
Ethernet werkt op zogenaamd 10BaseT (T voor twisted pair) verbindingen, met 10 Mb/s. Fast ethernet werkt op 100 Mb/s, en Gbit ethernet werkt al met 1 Gb/s.
De 10 Mb/s maakte maar slechts gedeeltelijk gebruik van de bandbreedte van een twisted pair gebalanceerde verbinding. Vandaar dat de kwaliteitseisen voor de kabels heel beperkt waren. Van de beschikbare 4 draden werden er twee gebruikt voor zenden en twee voor ontvangen. Dat noemen we half-duplex.
Voor fast ethernet zijn zogenaamde categorie 5 kabels nodig. Deze kabels (en connectoren en zenders en ontvangers) moeten aan hog(re) eisen voldoen om de hoge data snelheden te verwerken.
Er zijn diverse mogelijkheden om fast ethernet te bedrijven, varierend van full duplex met 4 draden tot twee keer half duplex. We kunnen zelfs verder gaan tot een 4-paar, ofwel een 8 draads geleider, zodat we 1Gb/s halen.

Voorbeeld 2: RS-485 en RS-422
Volgens de TIA/EIA-485-A (cq. 422) spec: RS 422: 1 Tx, 10 Rx, en RS 485: 32 Tx, 32 Rx Datasnelheid: 10 Mb/s, Maximale afstand: 1000 m. Common Mode Rejection: afhankelijk per component, typisch 5 tot 10 V common mode. Bekabeling: twisted pair, ongeveer 120 Ω karakteristieke impedantie. Hogere data snelheden betekent hogere slew rate (snellere stijgtijd), en dit produceert een hoger niveau aan harmonischen, met als gevolg meer EMI problemen. Transient beveiliging (ESD, bliksem, geschakelde inductieve last):
Shunting, via MOVs(metal oxide varistors), voor DM (tussen lijnen) en CM (naar aarde).
Isolatie, tegen CM: Optisch, Capacitief, Inductief (transformator)

Balanced, 2

- **Advantage**
  - **Cables are cheap compared to unbalanced (coaxial) cables**
- **Disadvantage**
  - **At IC or PCB level often more expensive due to extra (return)signal track**
- **Objective**
  - **Perfectly balanced output of driver**
  - **Perfectly balanced input of receiver**
  - **Perfectly symmetrical interface**
  - **No coupling with external fields (radiation into and out)**
- **These 'perfect' aspects will be discussed hereafter**

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Het voordeel van gebalanceerde verbindingen zijn de lage kosten, met name de aansluitkosten.

Het nadeel is de dubbele bedrading op PCB en IC niveau.

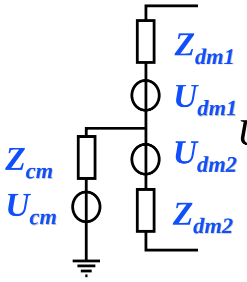
Om de goede EMI kwaliteit van gebalanceerde verbindingen te waarborgen moeten we

- •Goede kwaliteit driver toepassen; Dit betekent dat de uitgang erg goed gebalnceerd moet zijn
- •Goede kwaliteit ontvanger toepassen: Dit betekent een hoge onderdrukking van ongewenste signalen
- •Goede kwaliteit van verbinding en connectoren
- •Geen koppeling met de omgeving, voor wat betreft genereren van ongewenste elktromgantetische velden, en het gevoelig zijn tegen elektromagnetische velden

Deze 'goede' kwaliteit wordt in het hiernavolgende deel besproken

Balanced, driver output, 1

- Output of driver shall be perfectly balanced, i.e. only a signal <u>between the lines (DM)</u>, and no signal between lines and the reference (=ground) (CM)
- Therefore the common mode voltage shall be 0 $U_{cm}=0$
- By creating a high internal impedance Z_{cm} any common mode current will be minimized
- Furthermore, the differential mode sources shall be exactly in-phase



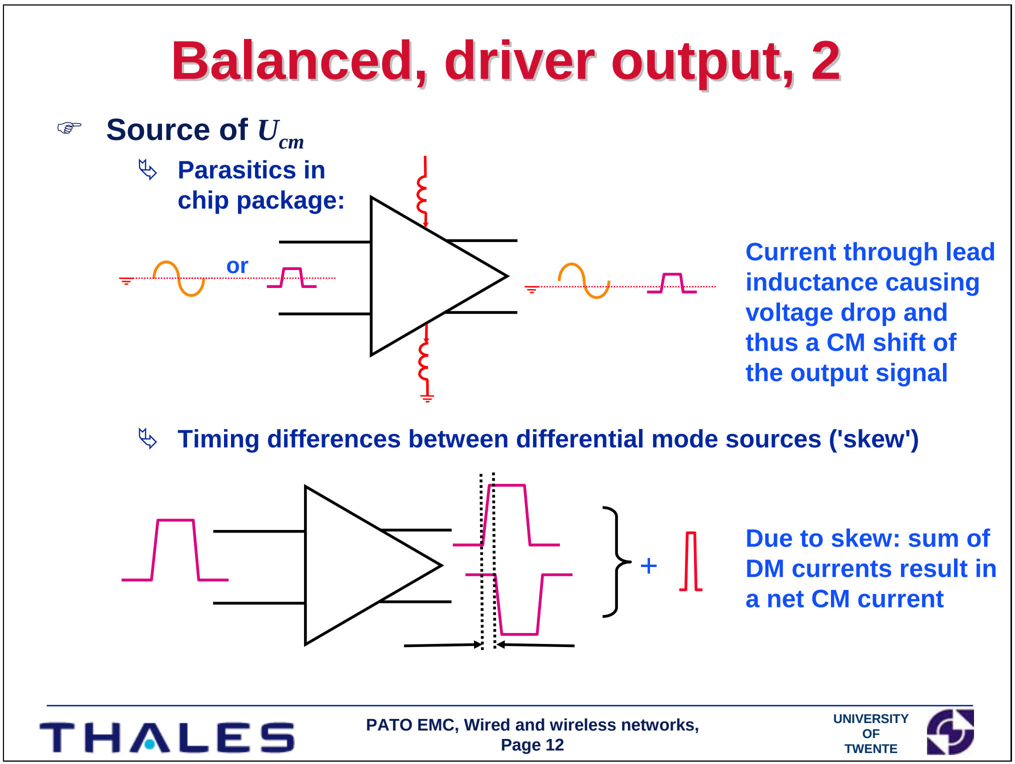
$$U_{dm} = U_{dm1} + U_{dm2}$$

Het signaal dat door een driver op een gebalanceerde verbinding wordt gezet moet geen common mode signaal bevatten. Immers, een common mode signaal is erg effectief (~60dB effectiever) in het genereren van ongewenste uitgestraalde velden.

Dit kan op diverse manieren gerealiseerd worden

- Heel hoge common mode impedantie, zodat er geen stroom kan vloeien
- Absolute symmetrie in de uitgangstrap

Natuurlijk moeten de DM bronnen in fase zijn!



Een common mode spanning wordt onder andere veroorzaakt door

- •Asymmetry in de uitgangstrap
- •Verkeerde behuizingen, waardoor de impedanties van de aansluitdraden een common mode spanning op de chip genereren
- •Verschil in timing tussen de NMOS en PMOS transistoren, waadoor er een verschil in de DM signalen is met als gevolg dat er een CM signaal wordt genereerd

Balanced, driver output, 3

- **Requirements**
  - **OSB > 60 dB (OSB= Output Signal Balance in TIA/EIA-568-B2)**
  - **Skew 0 ns**
- **Improvements**
  - **Common mode choke**
  - **Transformer**
- **Both improvements are (due to their parasitics) frequency- dependant solutions**
- **Therefore applied in the functional bandwidth**
  - **Audio: 20 Hz - 20 kHz**
  - **High-speed ethernet: 100 Mb/s**
- **EMI is broadband, so beware of the outband signals for example harmonics of a 100 Mb/s datasignal**

De TIA/EIA-568-B2 zegt:

Output Signal Balance (OSB), >50dB, waarbij de OSB=20Log(Vdm/Vcm)

De OSB is dus gedefinieerd als de verhouding van het uitgangs common mode signaal ten opzichte van het (gewenste) differential mode signaal.

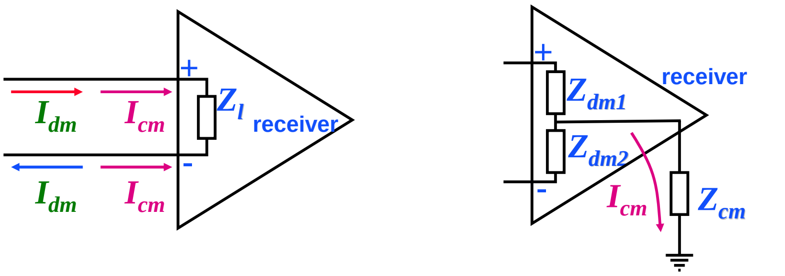
Dit geldt voor impedanties=50 Ω (niet in de praktijk….)

We kunnen de OSB van een (slechte) driver verbeteren door het toepassen van een common mode choke (twee goed gekoppelde spoelen in serie) of een transformator (twee goed gekoppelde spoelen 'parallel'). Meestal is een transformator onvermijdelijk.

Gezien de beperkte bandbreedte van het ferriet kernmateriaal in de spoelen is deze oplossing maar in een beperkt deel van het frequentie spectrum geldig.

Balanced, receiver input

- Input of a receiver shall be perfectly balanced



Ideal model: CM currents cancel out in load

actual model: CM currents create a common mode voltage over common impedance

- Common Mode Rejection Ratio (CMRR) well known
  - Opamps: decreasing with frequency
  - Digital circuits: frequency (band) limited

De ingang van een ontvanger moet ongewenste signalen kunnen onderdrukken. Dit noemen we de CMRR, ofwel de common mode rejection ratio.

Voor OpAmps worden wel eens getallen tot 10.000 (80 dB) genoemd. Dit geldt echter maar tot een bepaalde frequentie (enkele kHz). Voor digitale ontvangers wordt een hoge CMRR gerealiseerd door het perfect balanceren van de ingangstrap op de chip. Vaak is dit slechts mogelijk voor een beperkt frequentie bereik.

Voor RS-485 (10 Mb/s) kan worden volstaan met een directe verbinding van de interface op de chip. Voor fast ethernet kunnen we bijna niet zonder een ingangstrafo.

Balanced, interface

- Interface, including connectors, shall be perfectly symmetrical
- Often twisted pair (UTP: unshielded Twisted Pair) or Quad (2 pairs) are used
- The unwanted conversion of the transversal differential mode signal to the unwanted longitudinal signal is called LCL: longitudinal conversion loss
- Basic requirement is LCL<60dB
  - i.e. differential mode signal current of 10 mA generates 10 µA common mode current.
    This is higher than the basic design rule of 3 µA
- The connectors (RJ45) often destroy the quality
- Solutions: common mode chokes and transformers

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EN 55022 gaat uit van een PSTN wat wordt toegepast voor 200 Hz - 4 kHz audio signalen. De impedantie is 600 Ω.

Over dit netwerk wordt ook ADSL bedreven, in de 150 kHz - 3 MHz band. Voor deze frequenties is de impedantie 100 - 150 Ω.

De LCL mag voor categorie 3 bekabeling tussen 150 kHz en 1500 kHz 50dB bedragen

Voor categorie 5 moet dit 60dB zijn.

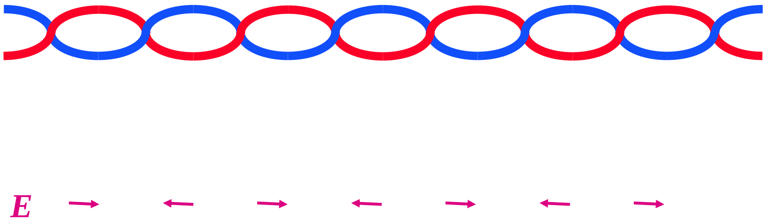
Tussen 1500 kHz en 30 MHz nemen deze echter af tot 25 dB respectievelijk 35 dB.

De LCL is een belangrijke parameter; Het geeft aan welk deel van het gewenste signaal (transversaal) als ongewenst signaal (longitudinaal) wordt genereerd. We kennen uit de voorgaande hoofdstukken al de regel dat 5 µA CM stroom een veld genereert dat de limietwaarde in normen kan overschrijden. Een DM stroom van 5 mA is heel gebruikelijk, en een LCL van bijvoorbeeld 40 dB levert daneen CM stroom van 50 µA op (5 mA, 40 dB, levert 50 µA).

De RJ-45 (ethernet etc.) connectoren blijken de kwaliteit van de verbinding vaak te verknallen.

Balanced, coupling with fields

- Trick: fields due to DM currents is very low
- Additional trick: twisting the interface (not possible with PCB tracks…)



Resulting field strength is reduced due to the cancelling effect of all segments

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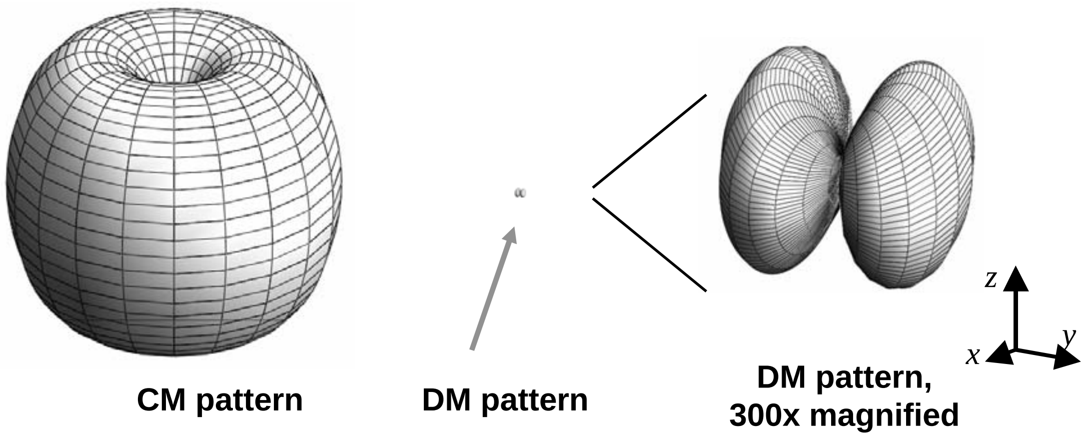
Remember the difference in CM and DM radiated emission



This is also the basic concept for using balanced lines:
The coupling from/into interfaces is a function of the separation s or h between the conductors. Remember the emission model derived from the basic dipole, and by adding a equal in amplitude, but directed in opposite direction (DM model):

$$\left|\hat{E}_{DM}\right| = 1.316\times10^{-14}\frac{\left|\hat{I}\right| f^2 L s}{r}$$

and the immunity model: $I_{TLM}(L) = \frac{2.Z_c.h.E_x}{D}[1-\cos\ \beta L - \frac{Z_s}{Z_c}\sin\beta L]$

so the coupling out of and into a network cable is a function of the distance between the conductors

Balanced

- Balanced interface nice: cheap, simple
- Symmetry (driver, receiver and interface) is very important
- Symmetry often optimized for a specific frequency (band) using
  - Common mode chokes
  - Transformer (or baluns: balanced-unbalanced)
  - Tuning of the driver and/or receiver
- But EMI is wide band; be aware of that!
- (EMI-) wrong applications
  - PLC: power line comm. (50 Hz network used upto 30 MHz)
  - ADSL: but properly handled (upto now) (dataline designed for 200-4000 Hz, now used upto some MHz)
- Extra barrier via a shield: shielded twisted pair (STP)
  actually a balanced interface in an unbalanced environment

Gebalanceerde verbindingen zijn de standaard verbindingen voor audio (baseband) en data.

Doordat de kabels er al liggen worden deze verbindingen ook voor andere toepassingen gebruikt.

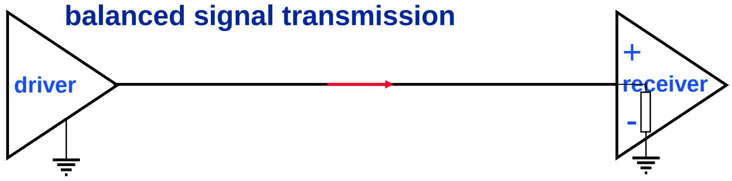
ISDN (integrated services digital network) maakt gebruik van twee draden, full-duplex, resulterend in 144 kb/s.

ADSL (asymmetric digital subscriber line) gebruikt een simplex 1.536 Mb/s verbinding naar de gebruiker, een simplex 9.6 kb/s link van gebruiker naar centrale, naast de 4kHz POTS twee-weg audio verbinding (POTS= plain old telephone service)

Power Line Communication is een techniek die inmiddels in Europa is afgezworen, maar door de amerikanen nog wordt onderzocht. Daarbij gebruiken ze het 50 Hz voedingsnetwerk en sturen datasignalen tot 30 MHz erover heen. Die signalen worden door de verspreide bekabeling van het 50 Hz netwerk uitgestraald en dit levert een enorme ethervervuiling op.

Unbalanced, 1

- Applications
  - Coaxial cables
  - IC structures
  - PCB structures
- Advantages
  - High-quality interface due to inherent shielding
  - Characteristic impedance much better, in %, than balanced lines, thus less reflections and signal distortion
  - In IC and PCB: due to the use of the ground as return conductor, the number of conductors is lower compared to balanced signal transmission

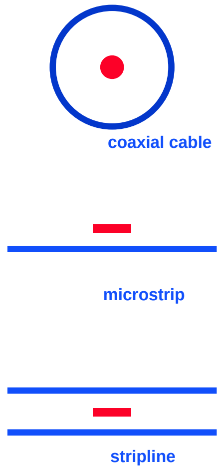


Ongebalanceerde verbindingen zijn eigenlijk superieur ten opzichte van de gebalanceerde verbindingen, al doet het voorvoegsel 'on' anders vermoeden.

De reden is dat een ongebalanceerde verbinding een veel grotere bandbreedte heeft dan welke andere koperdraad verbinding dan ook. Daarnaast gedraagt de mantel van een ongebalanceerde verbinding zich nog eens als een 'afscherming' en kan daardoor beter ongewenste velden buiten de mantel houden (voor hogere frequenties zodat de skindiepte voldoende is).

Unbalanced, 2

- Due to skineffect, the currents flows at the surface of the conductors
- Due to Lenz Law, the return current flows as close as possible to the signal current
- And, also due to Lenz law, any interfering (external) current flows at the outer surface of the interface
- This is called current splicing



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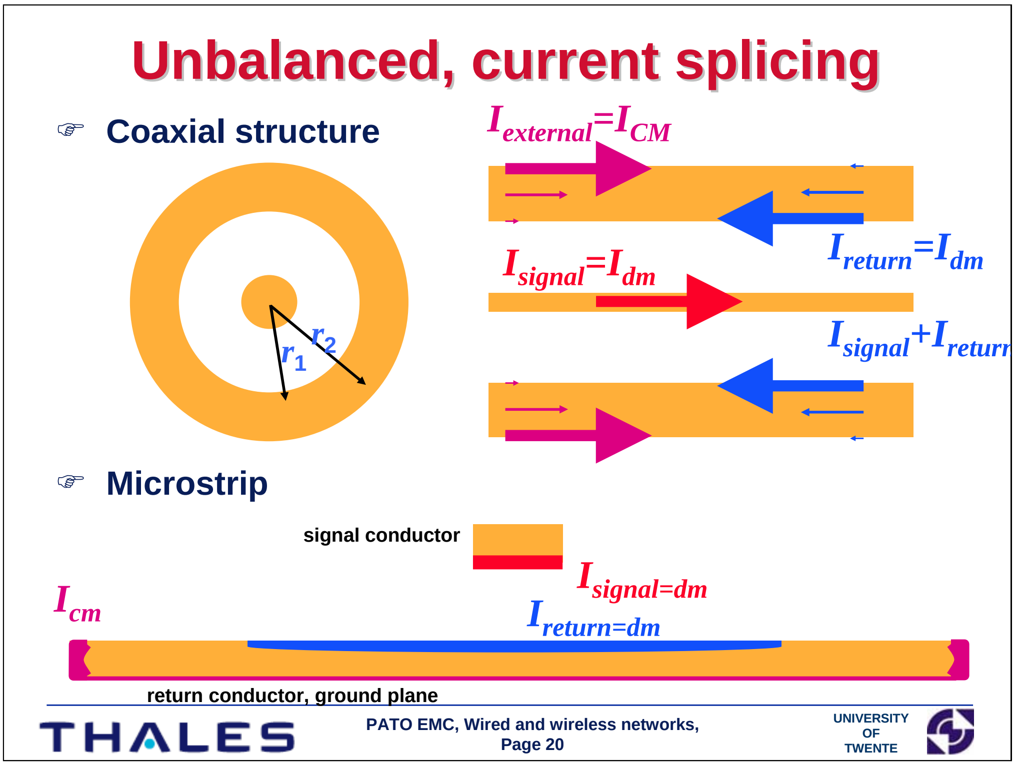
Lenz zegt: de stroom zoekt het pad met het kleinste lusoppervlak



Het storende signaal blijft aan de buitenkant van de kabel lopen, terwijl het gewenste signaal aan de binnenkant loopt. Daardoor lijkt het alsof we twee verschillende buitengeleiders hebben:

1. Voor het ongewenste signaal
2. Voor het gewenste signaal

Deze truc gaat ook op bij printed circuit boards: het gewenste signaal blijft dicht bij de signaal geleider, als gevolg van het proximity effect, en het blijft aan het oppervlak van de aardlaag als gevolg van het skin-effect.

Het ongewenste signaal daarentegen loopt helemaal aan de buitenkant van het aardvlak.

Unbalanced, current splicing

- Current splicing very effective due to the exponential behavior (as function of the frequency) of the skineffect
- Remember skineffect: 66µm at 1 MHz (copper). For
  - conventional coaxial cables: effective from appr. 100 kHz
  - 'superscreen' (mumetal shield): effective from appr. 1 kHz
  - PCBs: effective from approximately 3 MHz
  - ICs: effective from approximately 100 MHz
- Below this frequency no current splicing: current flows according Ohm's law and the common mode and differential mode currents are mixed (~common impedance crosstalk)

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Door het exponentiele gedrag van het skin-effect is current splicing zeer effectief

Skineffect: 66µm bij 1 MHz voor koper, dus

- •conventionele coaxiaal kabel: effectief vanaf circa 100 kHz
- •'superscreen' (mumetal shield): effectief vanaf circa 1 kHz
- •PCBs: effectief vanaf circa 3 MHz
- •ICs: effectief vanaf circa 100 MHz

Voor lagere frequenties lopen de stoor- en gewenste stroom parallel waardoor er common impedance (gemeenscahppelijke impedantie) overspraak optreedt.

Door gaten in kabels (gevlochten mantel) en in aardvlakken (VIAs e.d.) zijn de mantels niet ideaal, maar is er inductieve koppeling

Unbalanced, cable quality

- No equation for current splicing, but a widespread use of the term Transferimpedance, which confines more information
- Transferimpedance is, by definition, the ratio between the (longitudinal) common mode current and the (transversal) differential mode voltage between the lines

$$Z_{transfer} = \frac{U_{DM}}{I_{CM}}$$

- Note the correspondence with LCL (inside to outside) and SNT (inside to outside)

De term Transferimpedantie neemt alle effecten mee, zie hoofdstuk kabels

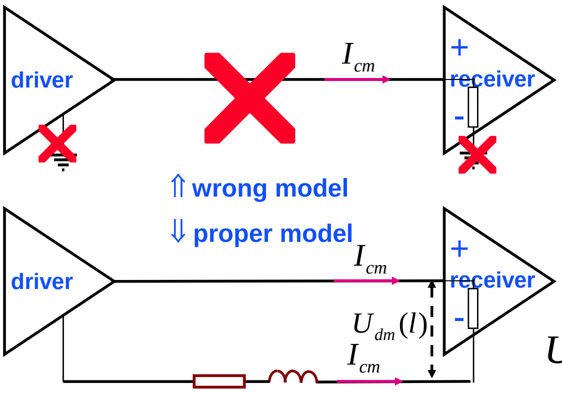
We hebben LCL (longitudinal conversion loss) en SNT (signal to noise transformation) niet uitgebreid kunnen behandelen.

LCL geeft aan welke deel van het DM signaal als CM signaal zichtbaar wordt, als gevolg van de beperkte kwaliteit van praktische verbindingen.

SNT geeft dit ook aan, maar veel exacter en voor een groter deel van het frequentie spectrum

Summary unbalanced, 1

- The conversion of <u>unwanted</u> (longitudinal) common mode currents into (transversal) differental mode voltage is controlled by the <u>transferimpedance</u>



$$U_{dm}(l) = U_{dm}(0) + I_{cm} Z_t$$

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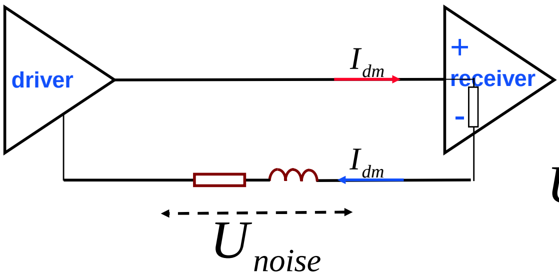
Summary unbalanced, 2

- And the reverse also: a (transversal) differential mode current creates via the transferimpedance a unwanted (longitudinal) noise voltage (SNT)



$$U_{noise} = I_{dm} Z_t$$

- This noise voltage drives the system which start to radiate

Comparison

- Balanced
  - At cable level cheaper
  - Intrinsic reduction of field coupling due to symmetry
  - Quality of driver, interface, connectors and receiver is important
  - Due to the limited bandwidth of the 'emergency fixes' (transformer, CM choke) the balanced interface is not suited for broadband data transmission
- Unbalanced
  - The quality of the shield or groundplane is important: Z_t
  - Not only the transferimpedance itself, but the ratio of the transferimpedance with respect to the loop impedance is important: asymmetry

- Remember: effect is reciprocal (field in interface, field from interface)

High speed networks

- What is high speed?
  - If the rise-time of a signal is shorter than the propagation of the signal
- Any discontinuity distorts the signal
  - Load impedance different from characteristic impedance of transmission line
  - Transmission line dimensions differs, such as Via or corner
  - Interconnections, such as connector-board, chip-package
  - Crossing of other transmission lines
  - Crosstalk
- Moore's law does not hold for data transmission!
  - Processor some GHz, databus hundreds of MHz
  - INTEL stopped and is looking for fiber-to-the-chip
- High-speed data transmission networks (ethernet): point-to-point (PtP, P2P) and switchers (star topology)

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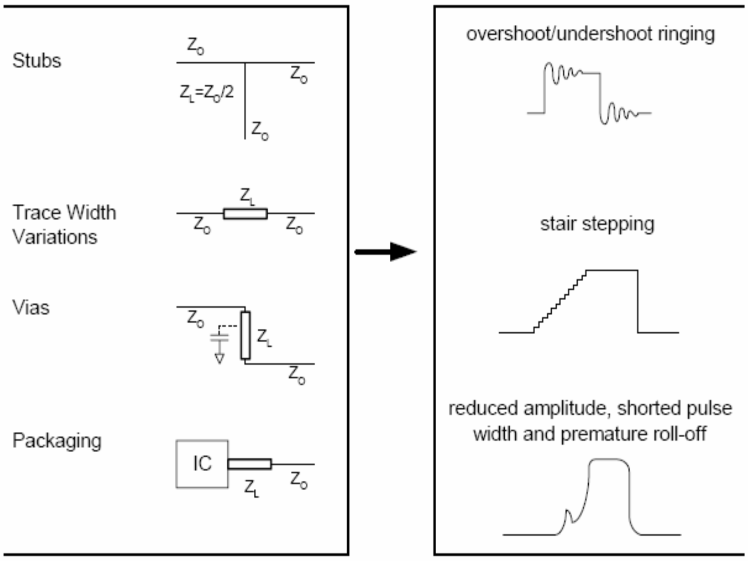


High speed networks

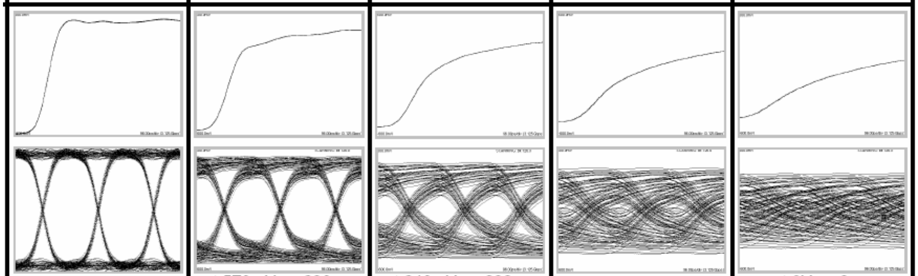
- Basic mitigation techniques have to be employed: no mismatch, termination, crosstalk reduction etc. etc.
- Signal Integrity is now a key issue in electronics industry!
- At high frequencies the skin-effect becomes more dominant, creating a large impedance
- The dielectric loss is alos not negligable anymore
- As a result, the signals are deteriorated, even in well controlled transmission lines
  - PCI Express (2.5 Gbps)
  - Infiniband (2.5 Gbps)
  - 10Gbase-X4 (3.125 Gbps)
  - Ethernet XAUI

A single PCI Express serial link is a dual-simplex connection, specified to speeds of up to 2.5Gbps per link that can be scaled in x1, x2, x4, x8, x12 x16 and x12 lane widths to achieve greater bandwidth.

Apart of PCI-Express other high-speed data transmission standards are known such as SATA, SAS, Fiber Channel, FireWire, DVI, HDMI, Infiniband (also called serial rapid IO), 10Gbase-X4, Ethernet XAUI

High speed networks

- **Effect:**

1meter 24AWG 3.125Gbps	5meter 24AWG 3.125Gbps	10meter 24AWG 3.125Gbps	15meter 24AWG 3.125Gbps	20meter 24AWG 3.125Gbps
				
⇳960mV ⇔300ps	⇳570mV ⇔280ps	⇳240mV ⇔200ps	⇳0V ⇔0s	⇳0V ⇔0ps

- **upper 1 rising slope, lower many bits (eye pattern)**
- **Eye pattern opening is a measure for data transmission quality**

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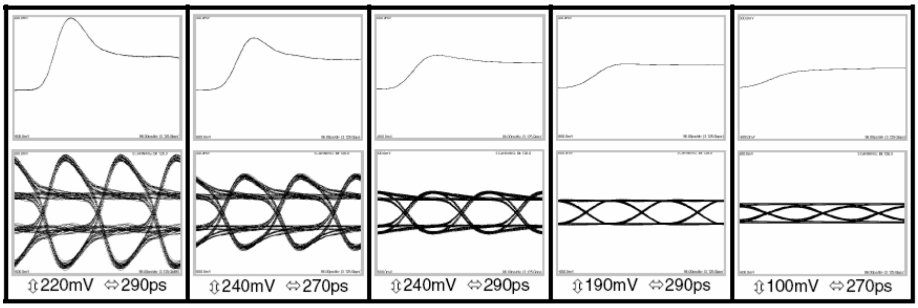
In the upper left cell, the output signal out of a 1 m long cable is presented. If we draw many of these signals, in a 1-0-1-0 pattern over eachother, then the eye-diagram as shown in the left-lower cell results. This eye-opening is very good: the larger the eye, the better it is, i.e. no distortion of the received signal. But if the cable is 5 meter long, the signal is distorted. In the upper graph, we can see that the rise-time is decreased, and that the (high-frequency) amplitude is decreased. This is caused by the skin-effect and the dielectric loss between the cable conductors.

The longer the cable, the worse the effect. If we look at the output signal of a 20 m long cable, we can see that the eye is closed, and no correct detection of the signal can be performed.

High speed networks

- Solution: equalisation:



- High frequencies are amplified to compensate the losses
- Passive equalisation: lower amplitude of signal
- Active equalisation: also compensation of amplitude

The effect of the distortion can be solved by using equalisers. An equaliser creates a so-called pre-emphasis by amplifying the high-frequency signals more that the low-frequency signals.

Equaliser can be bought of-the-shelf easily.

Available:

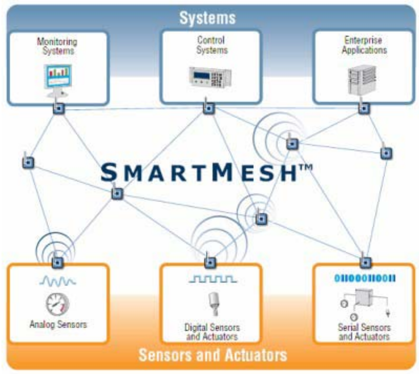
•Passive equaliser

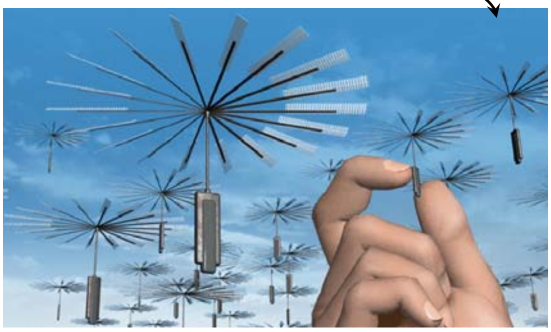
•Active equaliser, which als contains an amplifier

•Adaptive equaliser, which measures the propagation characteristic and adapts its pre-emphasis.

Trends in wireless

- Ad hoc networks, spontaneous communication
- Smart mesh
  (no base station needed
- Smart dust





- Smart antennas (later)

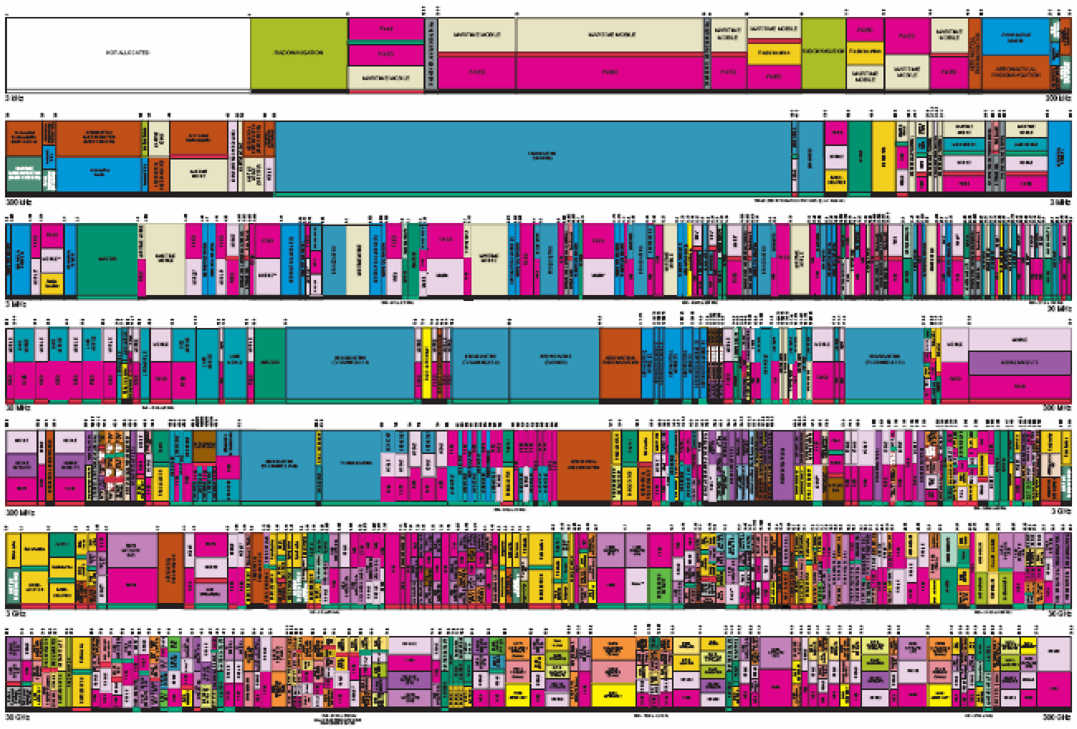
The conventional use of the spectrum was broadcasting or simplex connections. Now more and more short range radio systems are being used. The trend is towards spontaneous radiating elements, often connected to sensors, or in a network (smart mesh). The advantage of using a smart mesh is that the elements itself do not need high transmission power for the whole link, but the the messages are forwarded by other sensors in the (smart) mesh.

Another trend are the so-called smart antennas. These are actually very straightforward phased array antennas. The extra (smart) element is that the beam steering can be done in the digital domain (GSM), or by using an optical beamforming network, or by using phase shifters in all radiating elements.

Wireless networks, 1

- Many, many wireless application in use, and will be used in near future
- Old topic: find an open part of the electromagnetic spectrum
- Many negotiations, many delays, so a new phenomenon: use of the free bands, for example:
  - 2.4 GHz (Wireless LAN, Bluetooth), 3.5 GHz (WiMAX)
  - 5 GHz (HiperLAN)
- Problems
  - Interference between WLAN, Bluetooth, microwave oven etc.
  - Interference between strong transmitters, saturating the low-cost frontend of WLAN, BT etc. receivers
  - Multiple reflections (WiMAX instead of WLAN)
  - Ad-hoc communications disturbing other services

The EM spectrum:



Wireless networks, 2

- Propagation
- Reflections
- Interference
- Techniques to overcome interference

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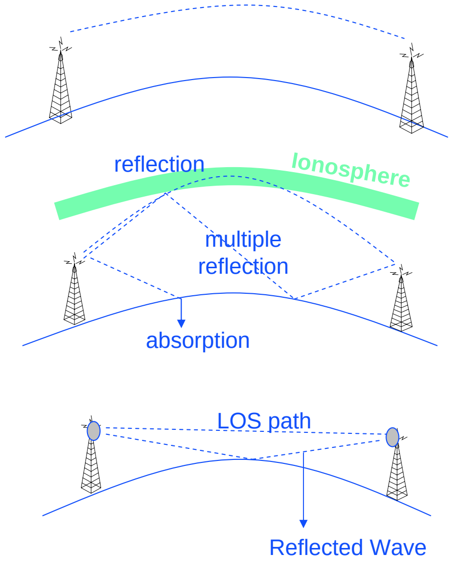
In this part we will discuss the impact of wireless networks on EMC issues. Basic understanding of propagation of electromagnetic waves, (multiple) reflections, interference and techniques to overcome interference will be discussed.

Propagation Modes

- Ground-wave propagation
- Sky-wave propagation
- Line-of-sight propagation
  - Path loss
  - (multiple) reflections
  - Fading due to moving users
  - Etc.



Ground wave propagation follows contour of the earth. It can propagate considerable distances, but often upto approximately 2 MHz only.
Examples: LF and MF radio (amplitude modulated) and long range communication.

Sky wave propagation uses reflection. At HF, the ground waves tend to be absorbed by the earth. Then the signal reflected from ionized layer of atmosphere (100-500km) back down to earth can be used. Signals can travel a number of hops, back and forth between ionosphere and earth's surface. The reflection effect is caused by refraction
Examples: Long range communication, amateur radio.

Line-of-Sight (LoS) propagation: At higher frequencies (the higher, the more), EM waves acts more as light. The EM waves:

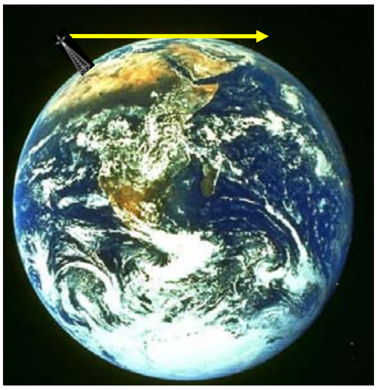
Above appr. 30 MHz, EM waves not reflected by ionosphere

Below appr. 1 GHz, EM waves will bend around obstacles

Above appr. 1 GHz, difficulty in passing obstacles

Transmitting and receiving antennas must be within line of sight. Often directional antennas are used. The reflected wave can interfere with the original signal.

Free-space Line-of-Sight



- Optical line of sight due to Earth's curvature: $d = 3.57\sqrt{h}$
- Effective (radio) line of sight

$$d = 3.57\sqrt{Kh}$$

  - d = distance between antenna and horizon (km)
  - h = antenna height (m)
  - K = adjustment factor to account for refraction (rainbow effect), rule of thumb 4/3
- Maximum distance between two antennas for LoS propagation: $d = 3.57\left(\sqrt{Kh_1} + \sqrt{Kh_2}\right)$
  - h_1 = height of antenna one
  - h_2 = height of antenna two

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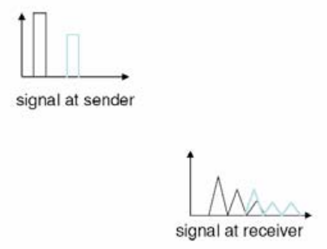
Free-space line of sight calculations are very straightforward and are based on the optical line of sight. The destructive interference due to summation of direct and reflected signal (via the Earth's surface) is not taken into account.

Propagation issues

- Atmospheric absorption
- Noise
- LoS propagation: Free space loss
- Reflection, diffraction, scattering
- Multipath propagation



Atmospheric absorption is caused by water vapor and oxygen, and worse at higher frequencies. For short range radio communication the atmospheric absorption is very low. Some windows, around 35-40 GHz and 95 GHz have very low absorption.

Thermal noise is caused by agitation of electrons, present in all electronic devices and transmission media, and cannot be eliminated. It is particularly significant for satellite communication. The noise is a function of temperature: amount of thermal noise in a bandwidth of 1Hz in any device or conductor is:

$$N_0 = kT \ (\mathrm{W/Hz})$$

N_0 = noise power density in watts per 1 Hz of bandwidth

k = Boltzmann's constant = 1.3803x10^{-23} J/K

T = temperature, in Kelvins (absolute temperature)

Thermal noise in a bandwidth of B Hertz (in watts)

$$N_{Watt} = kTB$$

Or: in decibel-milliwatts (dBm)

$$N_{dBm} = -114\mathrm{dBm} + 10\log(\mathrm{NF}) + 10\log B$$

Where $T = NFxT_0$, and T_0 = 290 degrees K, and

NF is effective noise figure of device

Other types of noise:

Intermodulation noise – occurs if signals with different frequencies share the same medium

Crosstalk – unwanted coupling between signal paths

Impulse noise – irregular pulses or noise spikes, short duration and of relatively high amplitude, caused by external electromagnetic disturbances, or faults and flaws in the communications system

LoS propagation, reflection, diffraction, scattering and multipath propagation will be discussed hereafter

Free-Space Propagation Model

- **Free space power received by a receiver antenna separated from a radiating transmitter antenna by a distance *d* is given by Friis free space equation:**

$$P_r = \frac{Ae_r}{\lambda}\frac{1}{d}\bullet\frac{Ae_t}{\lambda}\frac{1}{d}P_t$$

- **The gain *G* of an antenna is related to its affective aperture A_e**

$$G_r = \frac{4\pi Ae_r}{\lambda^2}$$

- **Thus:**

$$P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi d)^2}$$

- **Path loss, which represents signal attenuation as positive quantity measured in dB, is defined as the difference (in dB) between the effective transmitted power and the received power**

$$\text{PathLoss} = \text{PL} = 10\log P_r = 10\log(\frac{P_t G_t G_r \lambda^2}{(4\pi d)^2})$$

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Free-space propagation model is used to predict the received signal strength when transmitter and receiver have clear, unobstructed LoS path between them. Then the received power decays as a function of Tx-Rx separation distance: linear.

Later we will discuss the propagation in actual environments (no free space) and will see that the received power does not decay via a linear function, but to a higher power (n^2 ~n^5)

Path Loss: is the signal attenuation as a positive quantity measured in dB and defined as the difference (in dB) between the effective transmitter power and received power.

Free space power received by a receiver antenna separated from a radiating transmitter antenna by a distance *d* is given by Friis free space equation.

The gain *G* of an antenna is related to its affective aperture A_e

P_t is transmitted power
P_r is the received power at distance *d*
G_t is the transmitter antenna gain (dimensionless quantity)
G_r is the receiver antenna gain (dimensionless quantity)
d is Tx-Rx separation distance in meters
λ is wavelength in meters

Pathloss is term commonly used in the radio communication world

Propagation Models

- Modeling radio channel is important for:
  - Determining the coverage area of a transmitter
    - → Determine the transmitter power requirement
    - → Determine the battery lifetime
  - And: Finding modulation and coding schemes to improve the channel quality, and determine the maximum channel capacity
- Transmission path between sender and receiver could be
  - Line-of-Sight (LoS)
  - (partially) obstructed by buildings, mountains and foliage
- Variation of pathloss is called <u>fading</u>
- Even speed of motion effects the <u>fading</u> characteristics of the channel

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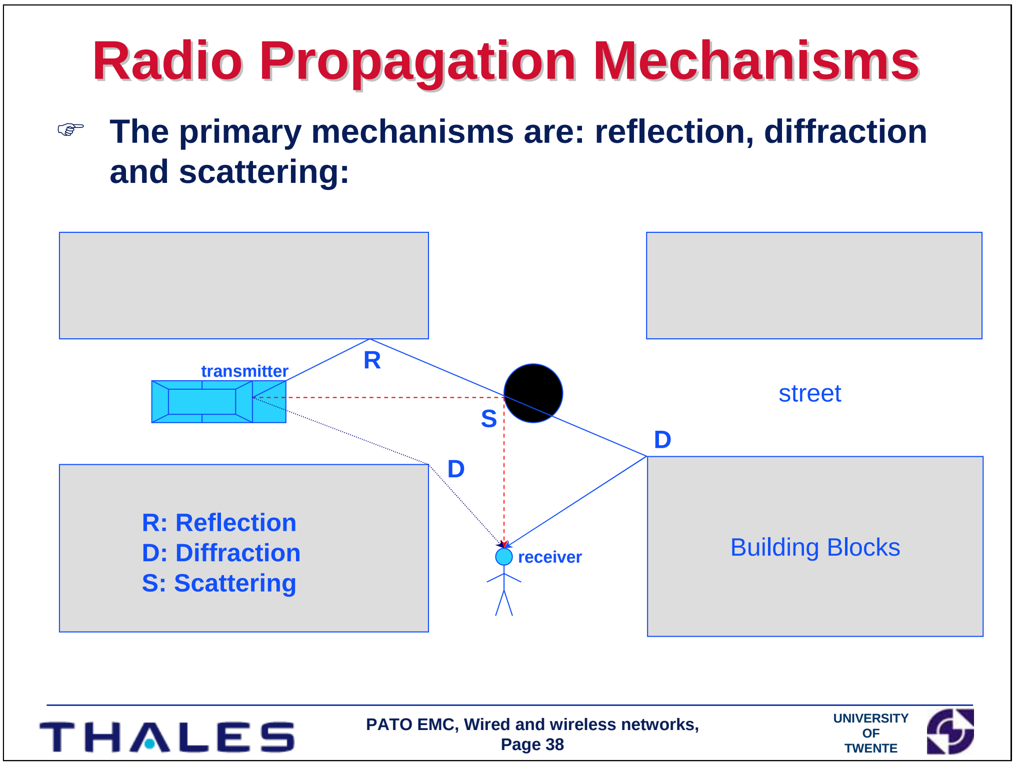
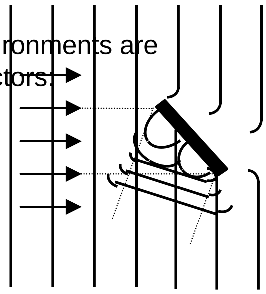
We are interested in propagation characteristics and models for EM waves, with frequency from some MHz to many GHz

This helps us to understand why mobile networks can be interfered (or not), and which parameters influence the quality of reception.

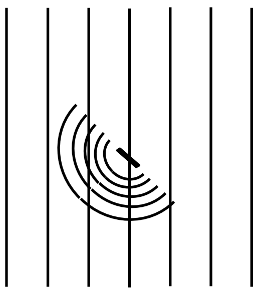


The physical mechanisms that govern radio propagation in actual environments are complex and diverse, but generally attributed to the following three factors:

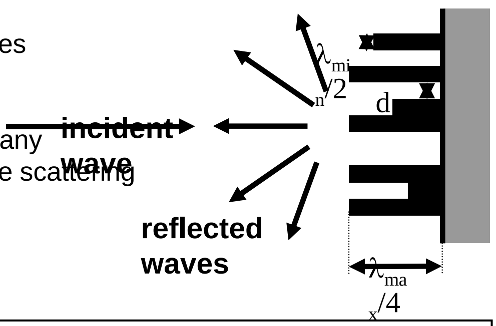


Reflection (Huygens' principle):
Occurs when waves impinges upon an obstruction that is much larger in size compared to the wavelength of the signal
Example: reflections from earth and buildings
These reflections may interfere with the original signal constructively or destructively

Diffraction and scattering (Rayleigh scattering):
Occurs when the radio path between sender and receiver is obstructed by an impenetrable body and by a surface with sharp irregularities (edges).
Explains how radio signals can travel through urban and rural environments without a line-of-sight path



Scattering:
Occurs when the radio channel contains objects whose sizes are on the order of the wavelength or less of the propagating wave and also when the number of obstacles are quite large.
They are produced by small objects, rough surfaces and other irregularities on the channel.
Follows same principles with diffraction.
Causes the transmitter energy to be radiated in many directions. Lamp posts and street signs may cause scattering



Radio Propagation Mechanisms

- Mobile moves: then the 3 mechanisms have an impact on the instantaneous received signal strength.
  - Clear line of sight path to the base-station, then diffraction and scattering will not dominate the propagation.
  - If a mobile is at a street level without LoS, then diffraction and scattering will probably dominate the propagation.
- As the mobile moves away from the transmitter over larger distances, the local average received signal will gradually decrease: the large scale path loss.
- The average large-scale path loss for an arbitrary Tx-Rx separation is expressed as a function of distance by using a path loss exponent n: $PL(dB) = PL(d_0) + 10n\log(\frac{d}{d_0})$
- The value of n depends on the propagation environment: for free space it is 2; when obstructions are present it has a larger value.

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As a mobile moves through a coverage area, these 3 mechanisms have an impact on the instantaneous received signal strength.
If a mobile does have a clear line of sight path to the base-station, than diffraction and scattering will not dominate the propagation.
If a mobile is at a street level without LoS, then diffraction and scattering will probably dominate the propagation.
Probability of reception: Rice distribution (direct wave modulated by a reflected wave)

As the mobile moves away from the transmitter over larger distances, the local average received signal will gradually decrease: the large scale path loss. Typically the local average received power is computed by averaging signal measurements over a measurement track of 5λ to 40λ. (For mobile phones, this means 1m-10m track)

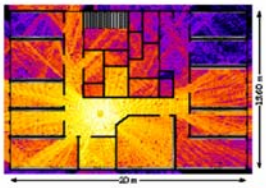
The models that predict the mean signal strength for an arbitrary-receiver transmitter (Tx-Rx) separation distance are called large-scale propagation models. These are based on Friis free-space equation.
For actual environments the Friis free-space equation is modified for higher loss than valid for free space. This is useful for estimating the coverage area of transmitters

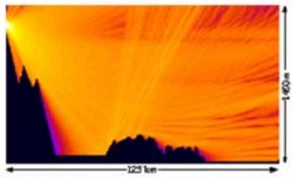
The average large-scale path loss for an arbitrary Tx-Rx separation is expressed as a function of distance by using a path loss exponent n:

$$PL(dB) = PL(d_0) + 10n\log(\frac{d}{d_0})$$

The value of n depends on the propagation environment: for free space it is 2; when obstructions are present it has a larger value.

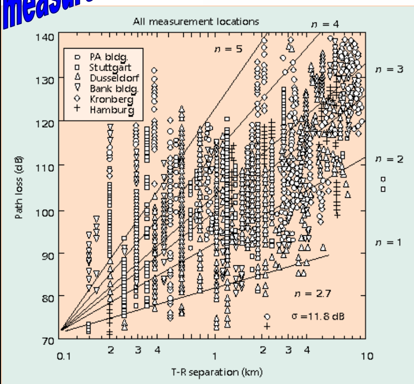
Path Loss for Different Environments





measurements

simulations



standards

Environment	Path Loss Exponent, *n*
Free space	2
Urban area cellular radio	2.7 to 3.5
Shadowed urban cellular radio	3 to 5
In building line-of-sight	1.6 to 1.8
Obstructed in building	4 to 6
Obstructed in factories	2 to 3

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Simulations in offices, cross-section near to a tower and a coverage map in a city. The effects of LoS, reflection, diffraction and scattering are obvious.

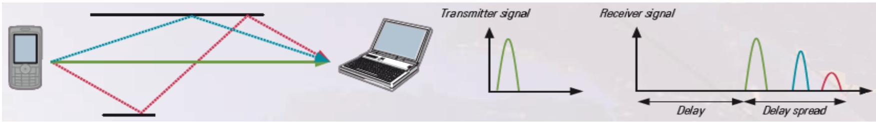
The measurements have been performed in german cities. It can be concluded that the coverage in specific areas should be seen as a general average.

The table gives the average large-scale path loss component *n* for an arbitrary Tx-Rx separation.
The value of *n* depends on the propagation environment: for free space it is 2; when obstructions are present it has a larger value.

An example how difficult propagation can be predicted in actual environments.

Multipath Propagation

- Due to multiple paths signals arriving at receiver at different phases and adding constructively and destructively in a random basis: multi-path propagation



- If phases add destructively, the signal level relative to noise declines, making detection more difficult: fading
- Other problem is the delay spread: the signals are spread in time of arrival at the receiver due to differences in path length, or often:
- Inter-symbol interference (ISI): One or more delayed copies of a pulse may arrive at the same time as the primary pulse for a subsequent bit
- WLAN, Bluetooth: more vulnerable. WiMAX is using OFDM
- Other effect is frequency spread(Doppler), due to fast moving object

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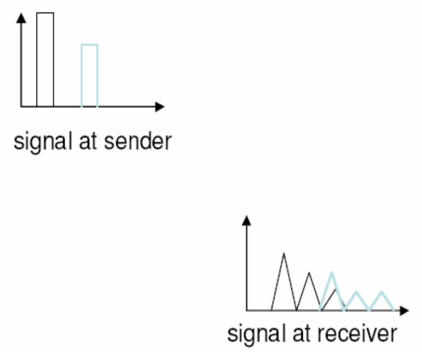
Remember Green's function (antennas): $\frac{e^{-j\beta d}}{d} = \frac{e^{-j2\pi\frac{d}{\lambda}}}{d}$

With this equation we can include the effects of reflection. The key factor is the (variation in) distance d with respect to the wavelength λ.

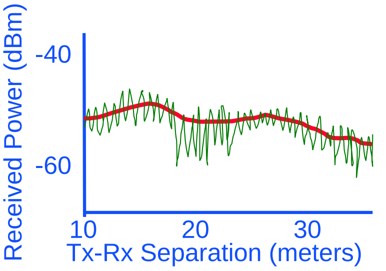
Inter-symbol interference (ISI) is the distortion of the wanted signal due to the reflected signals.



WLAN and E ave been designed for free space or limited reflective areas. WiMAX is an improvement, by making use of different modulation: Orthogonal Frequency Division Multiplexing (OFDM). By using different frequencies, i.e. wavelengths, at the sqame time, we can reconstruct the original signal easier.

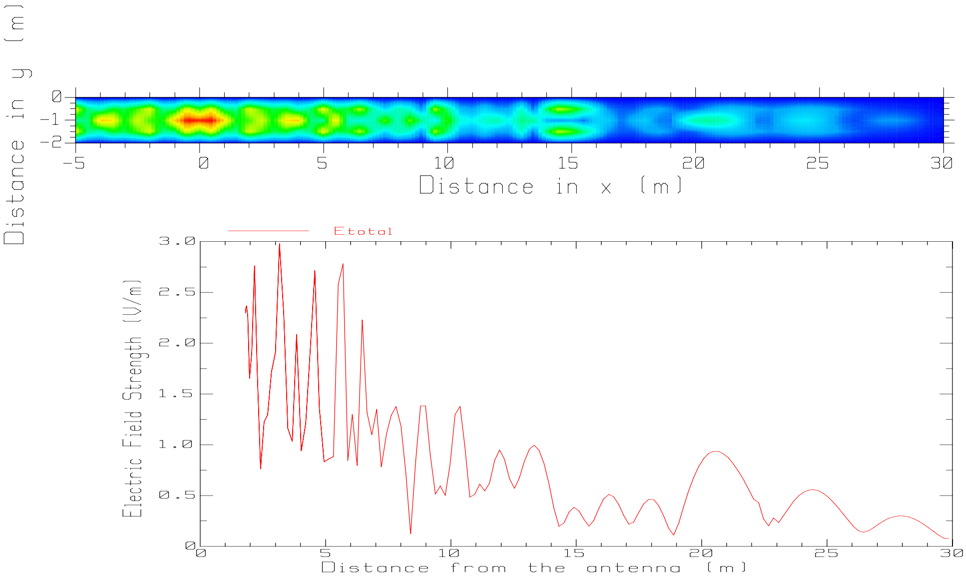
Fading

- Slow fading, shadow fading
  - Slower, as one moves and blockage and objects in between change, often modeled as a log normal distribution



- Fast fading
  - Due to small variations in path lengths as one moves or as scatterers move, often modeled as Rayleigh
  - In small scale fading, the received signal power may change as much as 3 or 4 orders of magnitude (30dB or 40dB), when the receiver is only moved a fraction of the wavelength
  - Fast fading, 'handled' somewhat with coding and diversity

Simulation: field distribution hallway



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Intersymbol interference

- For narrowband channels, i.e.
  BW (signal)<(Coherence) BW of channel: flat fading

- Broadband channels (TDMA, GSM, CDMA), i.e.
  BW (signal)>(Coherence) BW of channel: frequency selective fading
  - Causes ISI, some fading but not as bad as it averages out some
  - Fast fading 'handled' well with coding and diversity
    - Time diversity in Rake receivers for CDMA (combines multi path energies
  - ISI handled with equalizers in TDMA/GSM
  - CDMA codes separate multi path returns so no mixing, can combine

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If the signal has a narrow bandwidth, smaller than what is called the ''coherence bandwidth'' of the channel, we can assume flat fading. In other words, the signal does not change a lot in amplitude. For broadband signals we have to take into account the effect of the fading. Because the fading is very dependant of the variation in distance with respect to the wavelength, these effects are dominant in many systems operating above 1 GHz.

EMI mitigation techniques

- Adaptive Equalization for ISI. Concept equal to equalizers in high speed signal propagation in wired networks, except that due to the time-varying effect (moving objects), adaptive equalisers are needed
- Modulation and coding: sophisticated error-correction and detection codes to combat the effects of fading
- Diversity:
  - Space
  - Frequency
  - Time
- Smart antennas
- TFP concept

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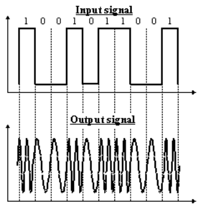
Adaptive equalization can be used to handle inter-symbol interference caused by multi-path propagation. It involves gathering dispersed symbol energy back into its original time interval. Similar to equalization in high-speed (wired) data communication systems. The dispersion is determined by maximum time delay spread (the time over which one symbol will affect other symbol)

Large variation, environment dependent. Outdoors in 5-100 μs range. Indoors in 0.1 to 1 μs. At 30kbps one bit is 33 μs long, so if delay spread is 100 μs it causes interference with 3 bits. At 200 kbps one bit is 5 μs long so 10 μs spread interferes with 2 bits. The higher the data rate the worse the ISI effect is.

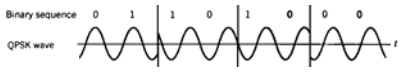
Channel coherence bandwidth B_c = (approx) 1/5x(RMS delay spread); Say delay spread = 4 μsec, B_c = 50 kHz, so AMPS at 30 kHz (so less) does NOT need equalizer but GSM at 200 kHz DOES. IEEE 801.11g WLAN allows 250 ns…
DSP algorithms, called equalizers, that estimate the channel transfer function and reverse its effects are used more and more. It involves a channel estimate via a known symbol sequence transmitted which is then compared at receiver with stored replica. Training and tracking….

Modulation

- Modulation: process of converting bits into signals
  - Frequency shift keying is used for FHSS: lower cost and easy operation



  - Quadrature phase-shift keying, used for low-data rate DSSS



- Orthogonal frequency division multiplexing (OFDM)
  - Multi-carrier modulation: one high-frequency carrier is replaced by multiple sub-carriers
  - The multiple sub-carriers are transmitted in parallel

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Modulation is the process of converting bits into analog signals. Many modulation techniques are known. In modern high-speed broadband systems OFDM is now the state of the art.

Orthogonal frequency division multiplexing (OFDM): Multi-carrier modulation: one high-frequency carrier is replaced by multiple sub-carriers. These multiple sub-carriers are transmitted in parallel. OFDM is much more suited for multiple reflecting environments because signals are transmitted in parallel at lower data rates, and thus multi-path delays are not as significant as for a single channel.

OFDM has typically a time guard of 800 ns, which is sufficient for channels with a delay spread upto 250 ns
(this is sufficient for office and home environments)

EMI mitigation: diversity techniques

- Diversity is based on the fact that individual channels experience independent fading events. This can be used to our advantage.

- Space diversity: techniques involving multiple physical transmission paths, e.g., multiple antennas (sometimes also mentioned as MIMO)
  - Most base stations have two diversity receive antennas for this reason
  - By selecting the strongest one can go from
    - 90% probability of not fading to
    - 99% with 2 antennas or
    - 99.99% with 4 diversity antennas

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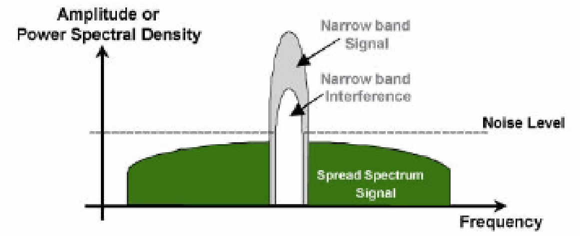
EMI mitigation: diversity techniques

- Frequency diversity
  - techniques where the signal is spread out over a larger frequency bandwidth or carried on multiple frequency carriers.
    - direct-sequence (WLAN) and
    - frequency hopping (Bluetooth)
    - coding (CDMA)



- Time diversity: techniques aimed at spreading the data out over time, e.g., bit repetition, interleaving, Rake processing (in CDMA)

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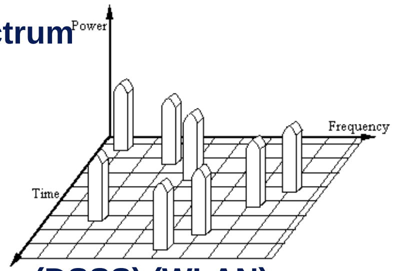
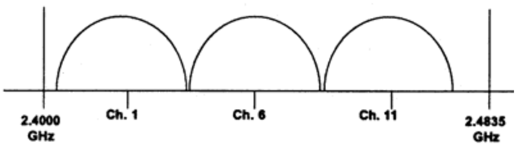
Diversity: spread spectrum

- Frequency hopping spread spectrum (FHSS) (Bluetooth)
  - Uses a narrowband carrier that shifts frequency in a pattern known by transmitter and receiver
  - Unintended receivers see the signal as impulse noise



- Direct sequence spread spectrum (DSSS) (WLAN)
  - Signal is multiplied by a pseudo-random code, known by transmitter and receiver
  - Unintended receivers see the signal as a broadband noise
  - Applied in WLAN 802.11
  - The channel bandwidth is 20 MHz. In 2.4 GHz range, three users can be simultaneously active



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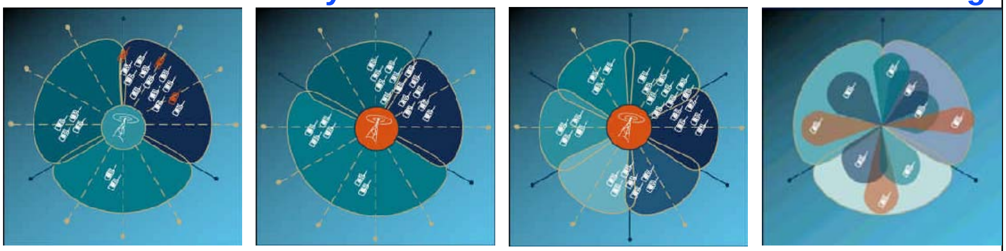
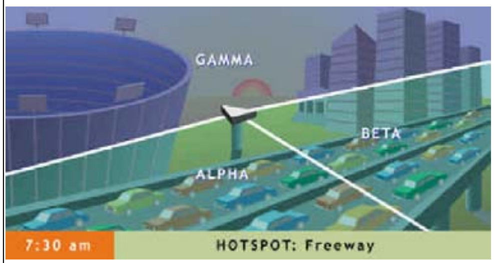
Arrays, mobile communication

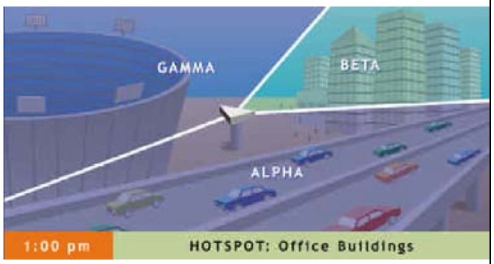
Traditional	Sector synthesis	Flexible sectorization	Adaptive beamforming

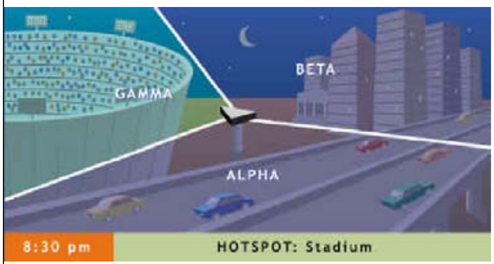


Unbalanced traffic	50% increase in capacity	90% increase in capacity	250% increase in capacity

Arrays, mobile comm., flex sectors







- Automatically adjust sector patterns to match traffic conditions conditions
- Set pattern changes according to time-of-day rules or
- Dynamic, real-time load balancing and performance optimization

performance optimization

Questions?

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