Lecture 2: Physical Layer Security

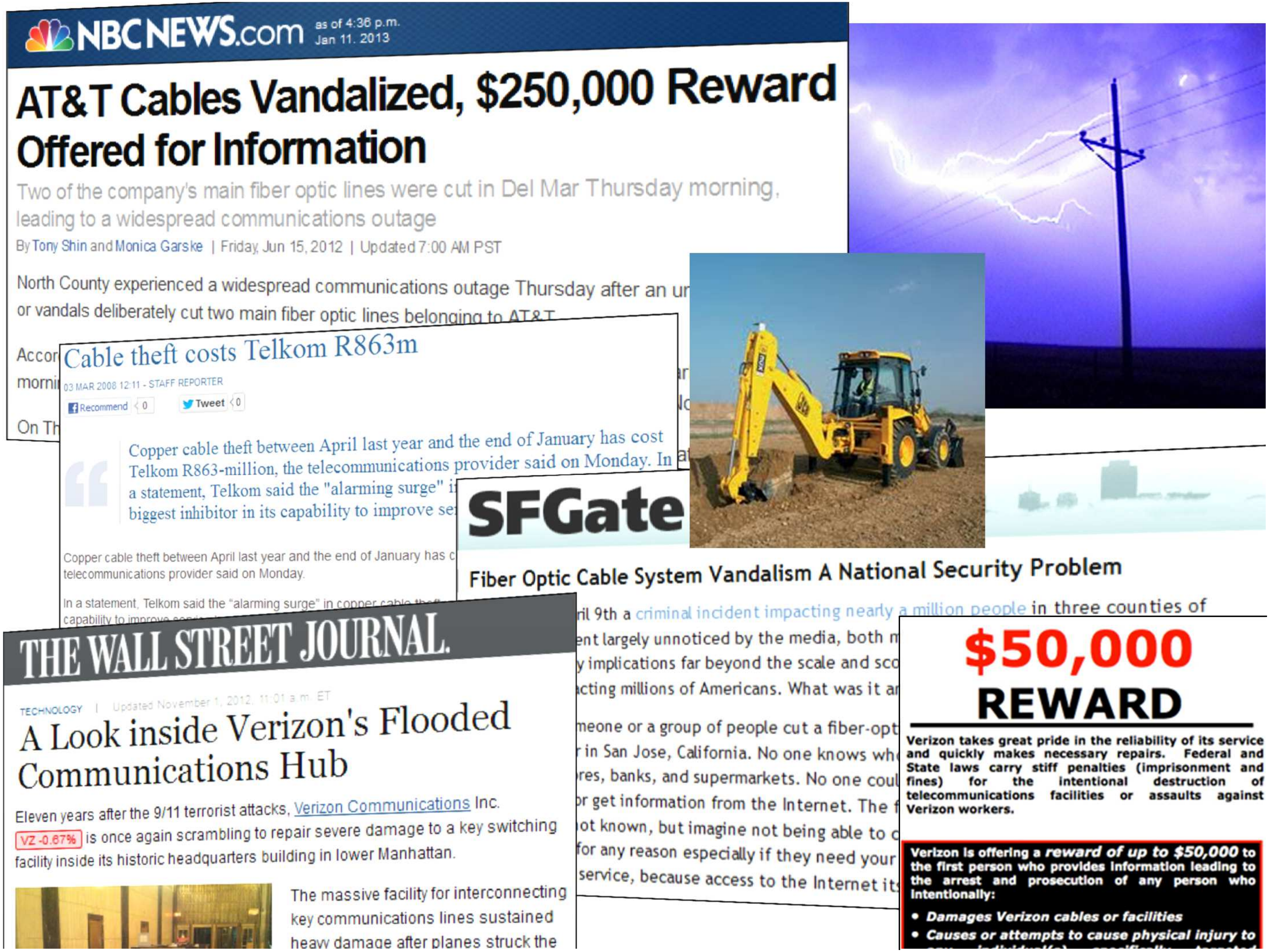
CS 598: Network Security

Matthew Caesar

January 17, 2013

Today: Security of the Physical Layer

- Networks are made up of devices and communication links
- Devices and links can be physically threatened
  - Vandalism, lightning, fire, excessive pull force, corrosion, wildlife, weardown
  - Wiretapping, crosstalk, jamming
- We need to make networks mechanically resilient and trustworthy



NBCNEWS.com as of 4:36 p.m. Jan 11, 2013

AT&T Cables Vandalized, $250,000 Reward Offered for Information

Two of the company's main fiber optic lines were cut in Del Mar Thursday morning, leading to a widespread communications outage

By Tony Shin and Monica Garske | Friday, Jun 15, 2012 | Updated 7:00 AM PST

North County experienced a widespread communications outage Thursday after an un
or vandals deliberately cut two main fiber optic lines belonging to AT&T

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Cable theft costs Telkom R863m

03 MAR 2008 12:11 - STAFF REPORTER

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> Copper cable theft between April last year and the end of January has cost Telkom R863-million, the telecommunications provider said on Monday. In a statement, Telkom said the "alarming surge" i
> biggest inhibitor in its capability to improve se

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capability to improve servic

SFGate

Fiber Optic Cable System Vandalism A National Security Problem

ril 9th a criminal incident impacting nearly a million people in three counties of
ent largely unnoticed by the media, both m
y implications far beyond the scale and sco
acting millions of Americans. What was it ar

meone or a group of people cut a fiber-opt
r in San Jose, California. No one knows wh
res, banks, and supermarkets. No one coul
or get information from the Internet. The f
ot known, but imagine not being able to c
for any reason especially if they need your
service, because access to the Internet it

THE WALL STREET JOURNAL.

TECHNOLOGY | Updated November 1, 2012, 11:01 a.m. ET

A Look inside Verizon's Flooded Communications Hub

Eleven years after the 9/11 terrorist attacks, Verizon Communications Inc. VZ -0.67% is once again scrambling to repair severe damage to a key switching facility inside its historic headquarters building in lower Manhattan.

The massive facility for interconnecting key communications lines sustained heavy damage after planes struck the

$50,000 REWARD

Verizon takes great pride in the reliability of its service and quickly makes necessary repairs. Federal and State laws carry stiff penalties (imprisonment and fines) for the intentional destruction of telecommunications facilities or assaults against Verizon workers.

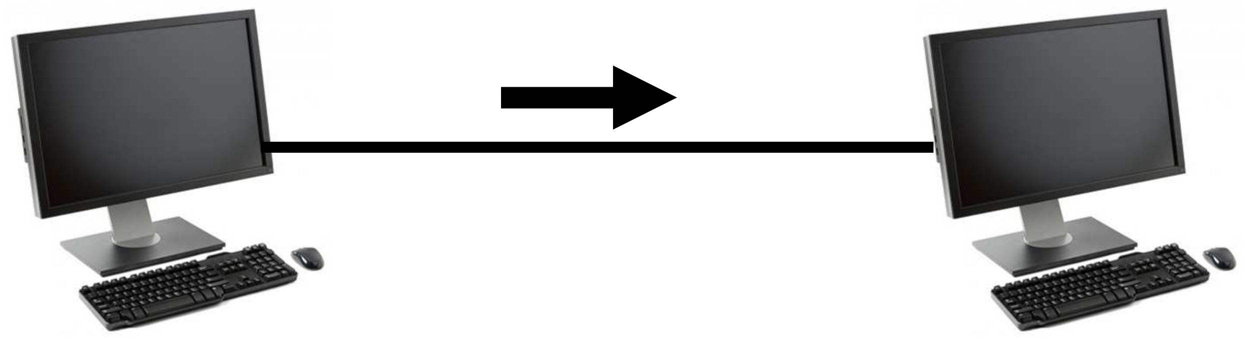
Verizon is offering a *reward of up to $50,000* to the first person who provides information leading to the arrest and prosecution of any person who intentionally:

- ***Damages Verizon cables or facilities***
- ***Causes or attempts to cause physical injury to***

This lecture

- Keeping physical communication secure
- Overview of copper, optical, and wireless communication technologies
- Wire mechanics, attacks, and countermeasures

How can two computers communicate?



- Encode information into physical “signals”
- Transmit those signals over a transmission medium

Types of Media

- Metal (e.g., copper)
- Light (e.g., optical fiber)
- EM/RF (e.g., wireless 802.11)

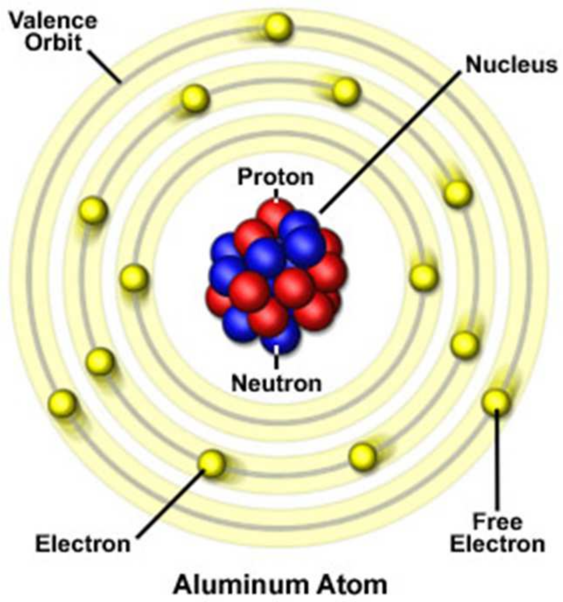
Security of Copper-based Networks

Making physical connections secure: Key Metrics

- Mechanical strength
  - Flex life, Breaking strength, torsional and compression strength, flammability, specific gravity, ease of deployment (stripping/termination), corrosion resistance, temperature requirements
- Noise/RF interference protection
- Cost

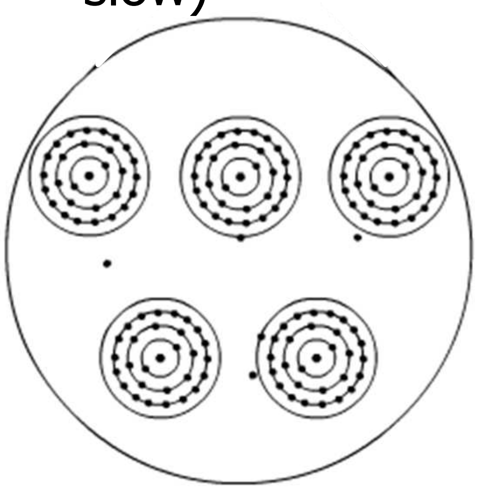
Background: Atoms

- Made up of positively-charged protons, negatively-charged electrons and Neutrons
- Electrons contained in orbits
- Highest orbit is called the valence shell
- Valence electrons can break off, forming free electrons

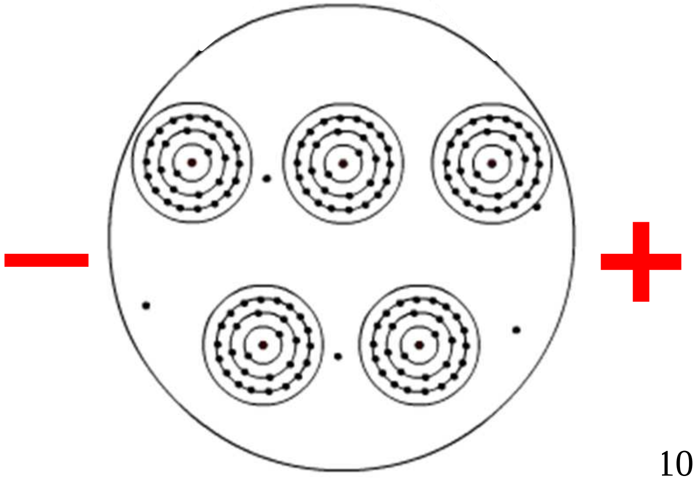


Background: Electrical Current

- Usually free electrons hop around randomly
- However, outside forces can encourage them to flow in a particular direction
  - Magnetic field, charge differential
  - This is called current
  - We can vary properties of current to transmit information (via waves, like dominos, as electron drift velocities are very slow)



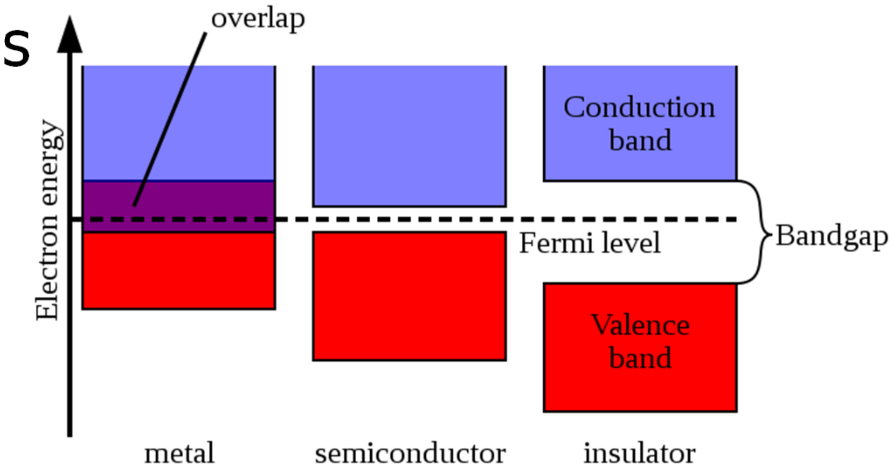
No charge differential



Charge differential

Conductors vs. Insulators

- Conductor: valence electrons wander around easily
  - Copper, Aluminum
  - Used to carry signal in cables
- Insulator: valence electrons tightly bound to nucleus
  - Glass, plastic, rubber
  - Separates conductors physically and electrically
- Semiconductor: conductivity between insulator and conductor
  - Can be easily made more conductive by adding impurities



Material	Resistivity (ohm m)
Glass	10^{12}
Mica	$9*10^{13}$
Quartz	$5*10^{16}$
Copper	$5*10^{-8}$

Common Conductors

- Aluminum: lightweight and cheap, but less conductive than copper
- Silver: most conductive material, but very high price
- Nickel: improved strength, higher resistance
- Tin: improved durability and strength, but higher resistance
- Copper: cheap, lower operating temperature, lower strength

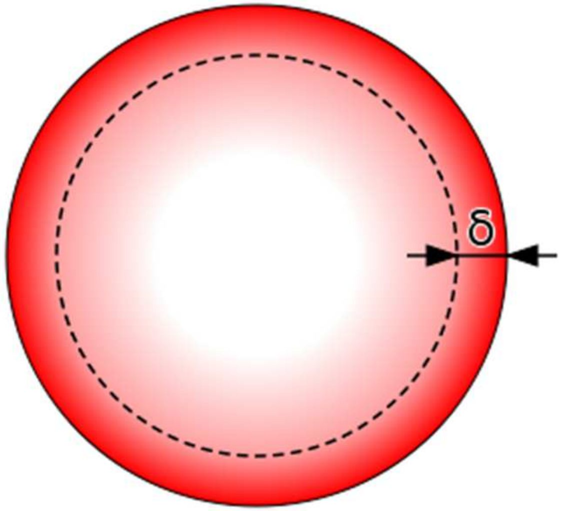
Coating Copper to Improve Resilience

- Coating copper can provide additional properties
  - Done by “hot dipping” or electroplating

- Tinned copper: corrosion protection, easier to solder
  - Industrial ethernet deployments, environments exposed to water such as ships
- Silver plated copper: better conduction, operation over wider temperature range (-65°C to 200°C). Commonly used in aerospace applications
- Nickel-plated copper: corrosion protection, operation over wider temperature range (thick plating can withstand 750 deg C), reduced high-frequency loss

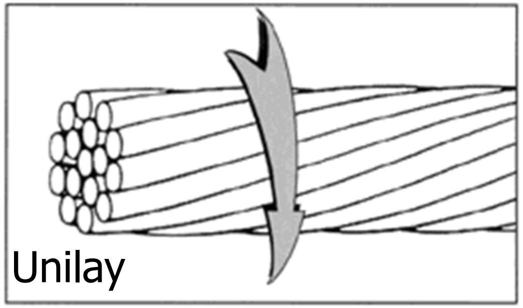
Reducing Resistance from the Skin Effect

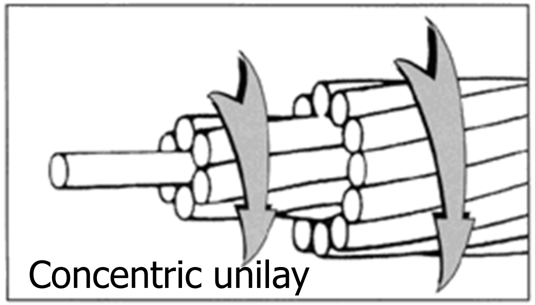
- Alternating electric current flows mainly at the "skin" of the conductor
  - Due to "turbulent" eddy currents caused by changing magnetic field
- Stranding helps, but not as much as you might think
  - Touching surface area acts like single conductor
  - Individually-insulating strands (Litz wire) helps
- Coating with low-resistance material can leverage this property
  - E.g., silver-tinned copper

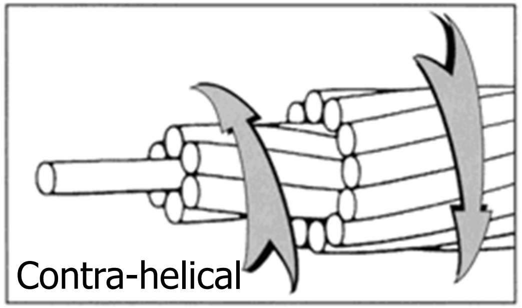


Improving Strength with Stranding

- Solid vs Stranded conductors
  - Solid: Inexpensive and tough, solid seating into jacks and insulation
  - Stranded: Increased flexibility and flex-fatigue life, increased conductivity
- Stranding type affects wire properties
  - Bunched: Inexpensive and simple to build, can be bulkier (circle packing problem)
  - Concentric:
    - Unilay: lighter weight and smaller diameter; greater torsional flex
    - Contra-helical: Greater mechanical strength and crush resistance; greater continuous flex
    - More twists → improve strength
- Ethernet comes in both solid (plenum) and stranded (standard)

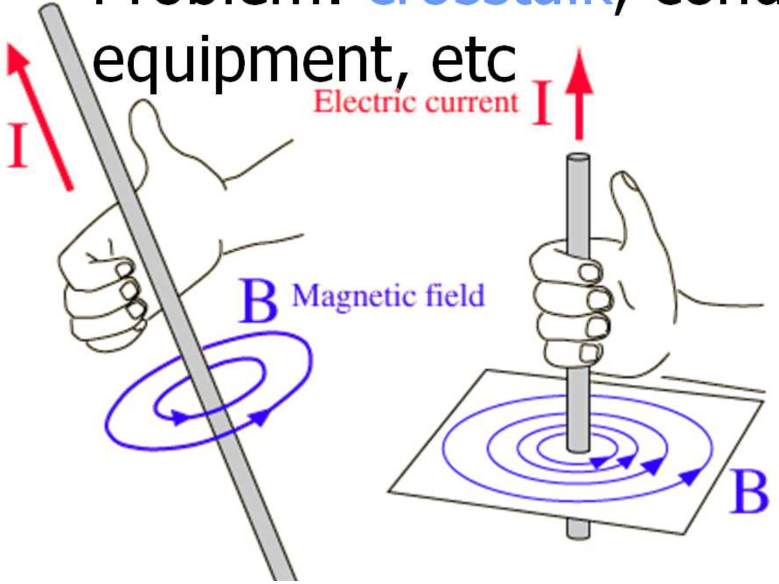


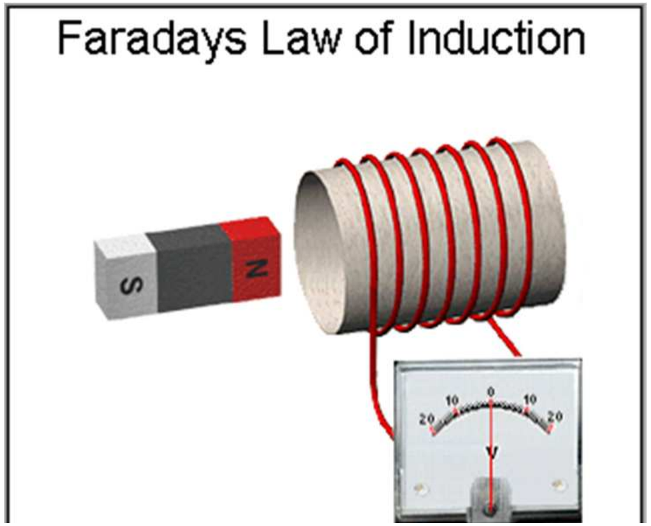




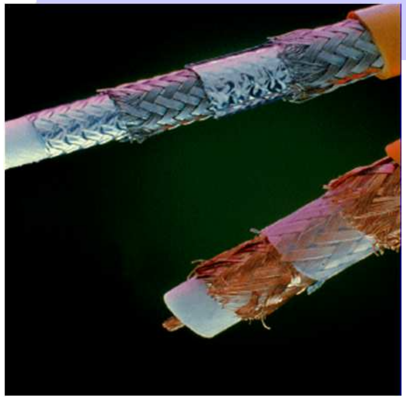
Noise, Jamming, and Information Leakage

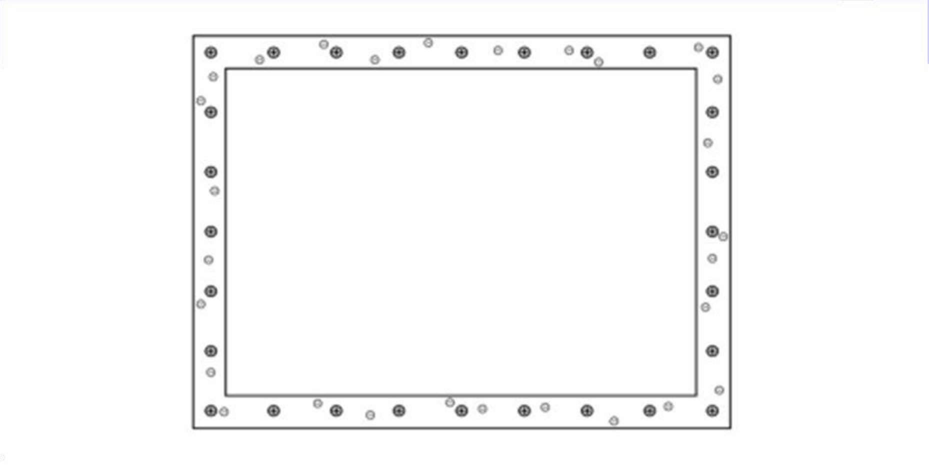
- When you move a conductor through a magnetic field, electric current is induced (electromagnetic induction)
  - EMI is produced from other wires, devices
  - Induces current fluctuations in conductor
  - Problem: crosstalk, conducting noise to equipment, etc



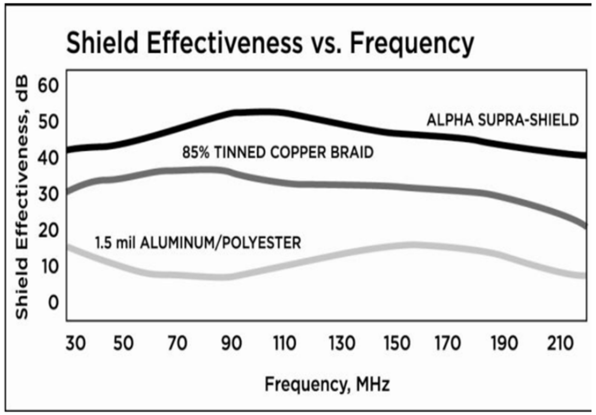


Reducing Noise with Shielding

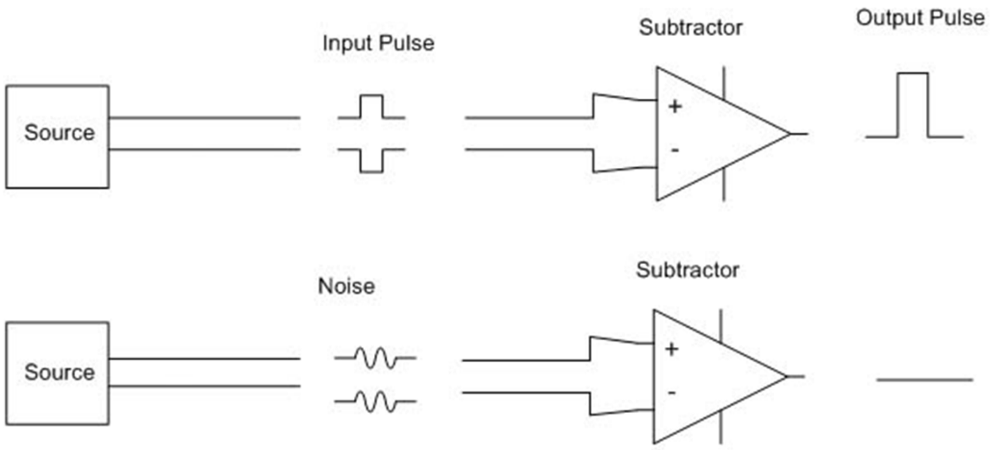


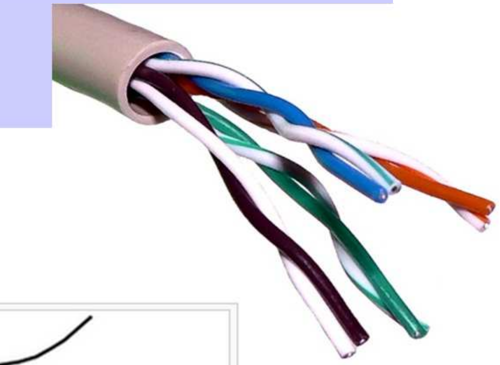


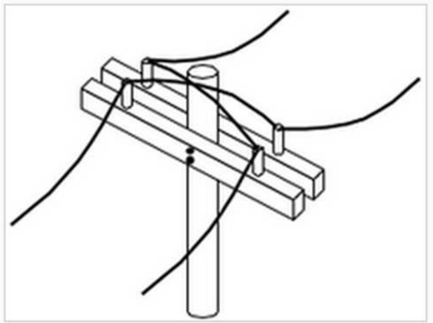
- Enclose insulated conductor with an additional conductive layer (shield)
  - Reflect, absorb (Faraday cage), or conduct EMF to ground
- Types of shielding
  - Metallic foil vs. Braid shield
    - Foil is cheaper but poorer flex lifetime
    - Braid for low freq and EMI, Foil for high freq and RFI
    - Foil widely used in commodity Ethernet
    - Combining foil+braid gives best shielding



Reducing noise with Twisted Pairing



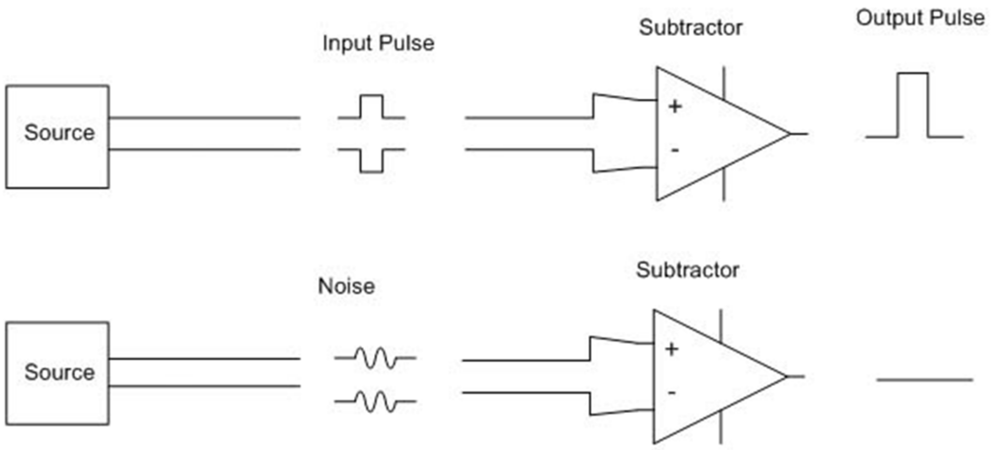


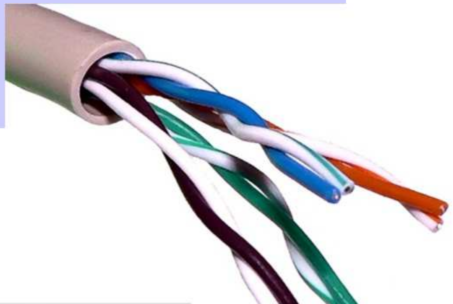


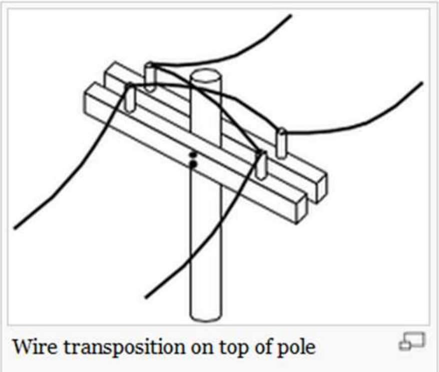
Wire transposition on top of pole

- Differential signaling: transmit complementary signals on two different wires
  - Noise tends to affect both wires together, doesn't change relative difference between signals
  - Receiver reads information as difference between wires
  - Part of Ethernet standard, Telegraph wires were first twisted pair

Reducing noise with Twisted Pairing







Wire transposition on top of pole

- Disadvantages:
  - EMI protection depends on pair twisting staying intact → stringent requirements for maximum pulling tension and minimum bend radius (bonded TP can help)
  - Twisted pairs in cable often have different # of twists per meter → color defects and ghosting on video (CCTV)

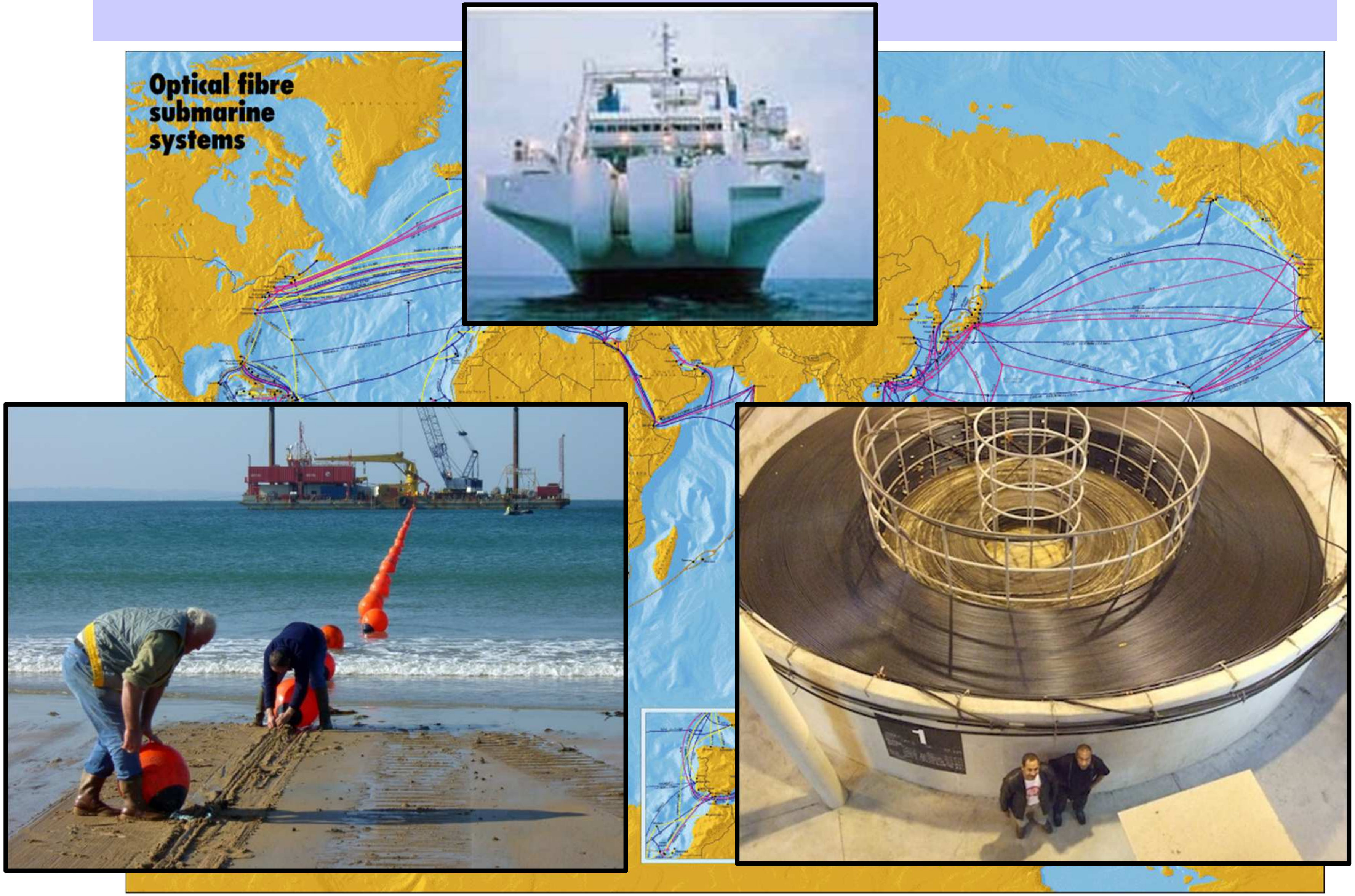
Insulators

- Insulators separate conductors, electrically and physically
- Avoid air gaps: ionization of air can degrade cable quality
- …

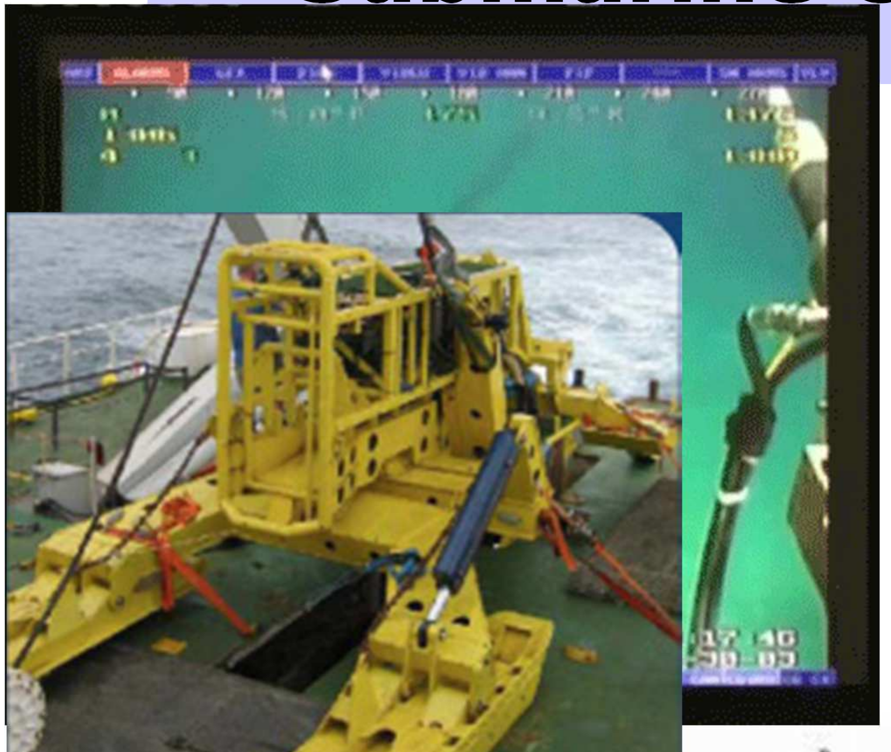
Cable Ratings

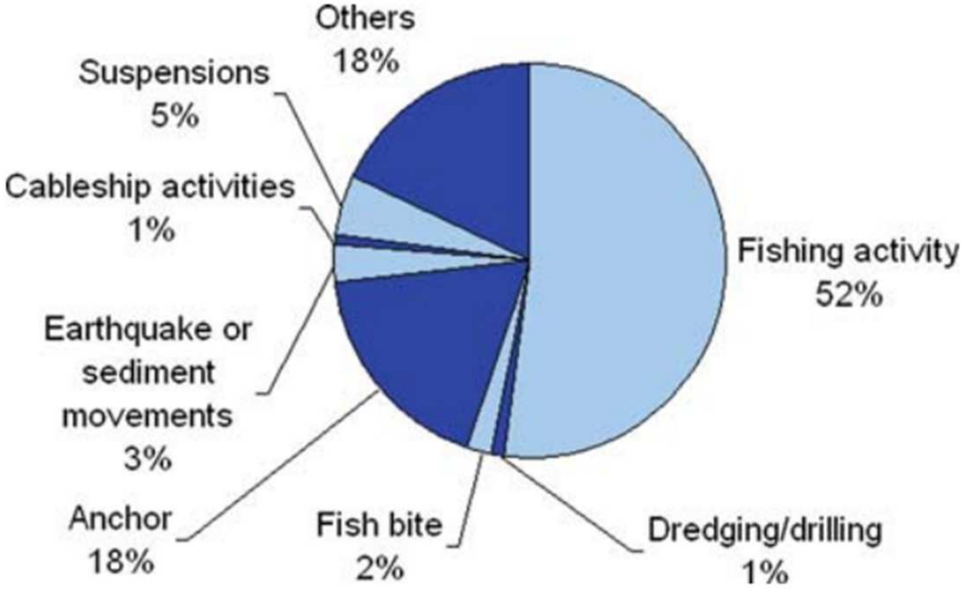
- Plenum rated (toughest rating)
  - National Fire Protection Standard (NFPA) 90A
  - Jacketed with fire-retardant plastic (either low-smoke PVC or FEP)
  - Cables include rope or polymer filament with high tensile strength, helping to support weight of dangling cables
  - Solid cable instead of stranded
  - Restrictions on chemicals for manufacture of sheath → reduced flexibility, higher bend radius, and higher cost
- Riser cable: cable that rises between floors in non-plenum areas
- Low smoke zero halogen: eliminates toxic gases when burning, for enclosed areas with poor ventilation or around sensitive equipment

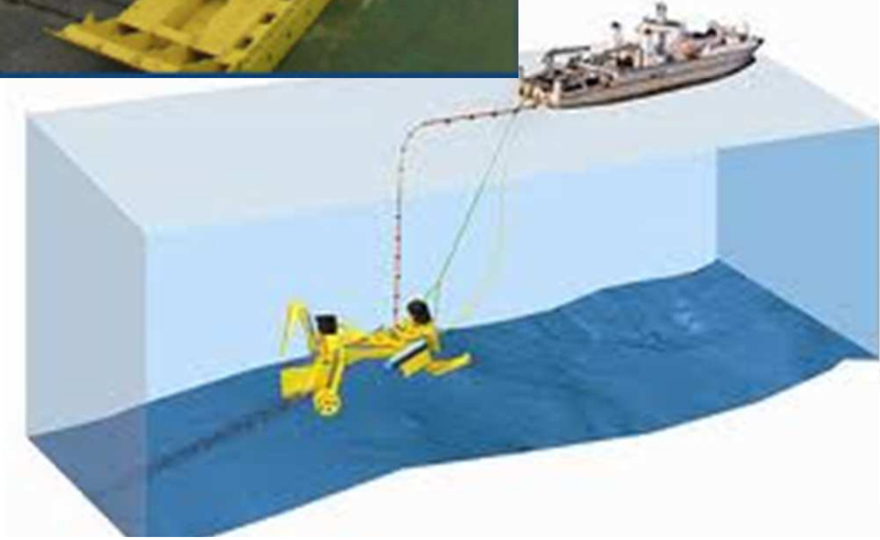
Submarine Cabling

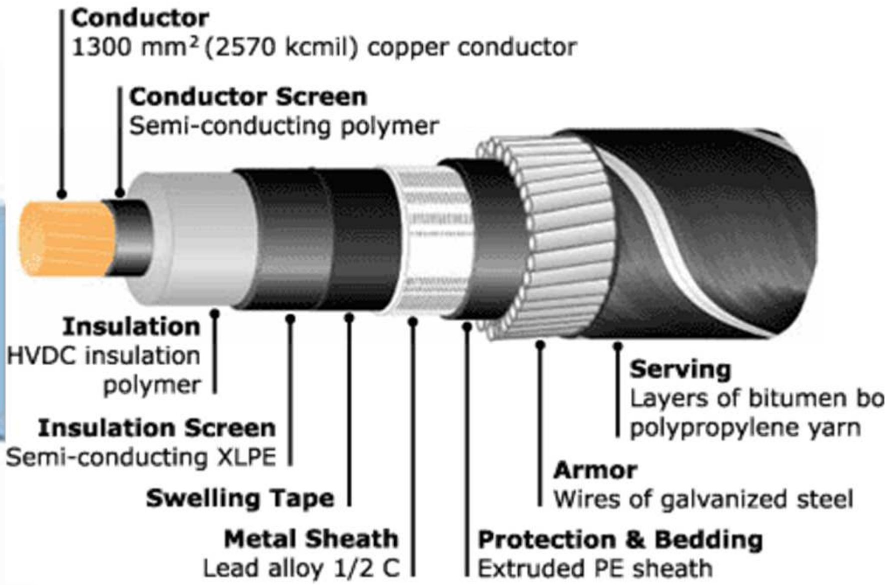


Submarine Cabling: Threats





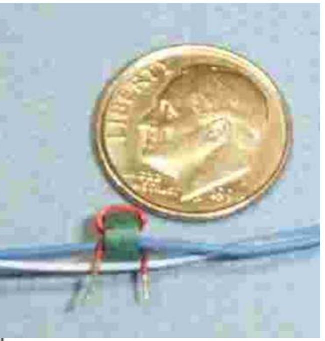


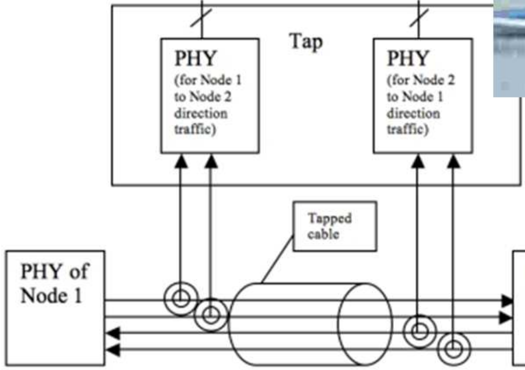


Physical Tapping

- Conductive Taps
  - Form conductive connection with cable

- Inductive Taps
  - Passively read signal from EM induction
  - No need for any direct physical connection
  - Harder to detect
  - Harder to do with non-electric conductors (eg fiber optics)




Tap
PHY
(for Node 1 to Node 2 direction traffic)
PHY
(for Node 2 to Node 1 direction traffic)
Tapped cable
PHY of Node 1
PHY of Node 2

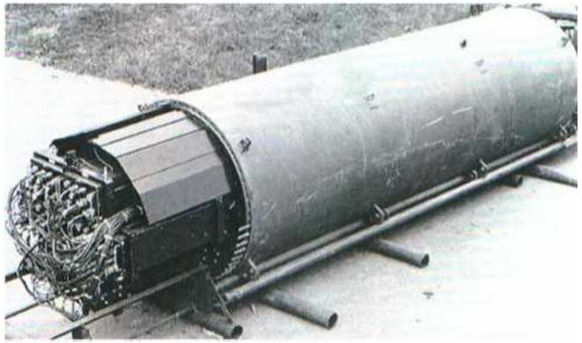
Tapping Cable: Countermeaures

- Physical inspection
- Physical protection
  - E.g., encase cable in pressurized gas
- Use faster bitrate
- Monitor electrical properties of cable
  - TDR: sort of like a hard-wired radar
  - Power monitoring, spectrum analysis
  - More on this later in this lecture

Case Study: Submarine Cable (Ivy Bells)

USSR
Sea of Okhotsk

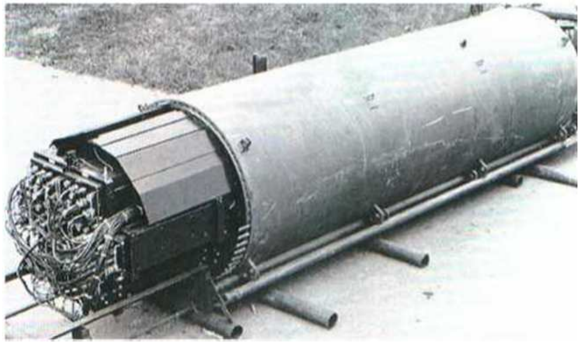
- 1970: US learned of USSR undersea cable
  - Connected Soviet naval base to fleet headquarters
- Joint US Navy, NSA, CIA operation to tap cable in 1971
- Saturation divers installed a 3-foot long tapping device
  - Coil-based design, wrapped around cable to register signals by induction
  - Signals recorded on tapes that were collected at regular intervals
  - Communication on cable was unencrypted
  - Recording tapes collected by divers monthly



Case Study: Submarine Cable (Ivy Bells)

USSR
Sea of Okhotsk

- 1972: Bell Labs develops next-gen tapping device
  - 20 feet long, 6 tons, nuclear power source
  - Enabled
- No detection for over a decade
  - Compromise to Soviets by Robert Pelton, former employee of NSA
- Cable-tapping operations continue
  - Tapping expanded into Pacific ocean (1980) and Mediterranean (1985)
  - USS Parche refitted to accommodate tapping equipment, presidential commendations every year from 1994-97
  - Continues in operation to today, but targets since 1990 remain classified



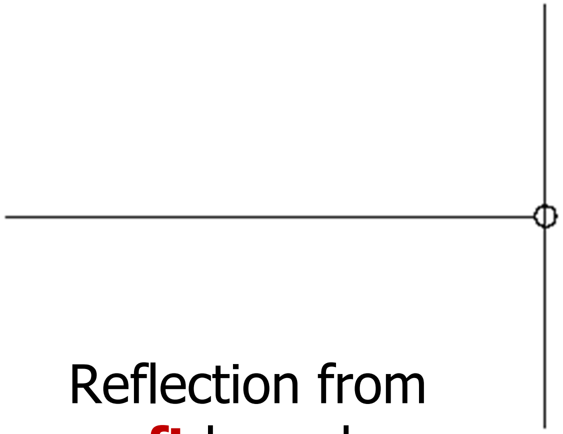
Locating Anomalies with Time-Domain Reflectometry (TDR)

- A tool that can detect and localize variations in a cable
  - Deformations, cuts, splice taps, crushed cable, termination points, sloppy installations, etc.
  - Anything that changes impedance
- Main idea: send pulse down wire and measure reflections
  - Delay of reflection localizes location of anomaly
  - Structure of reflection gives information about type of anomaly

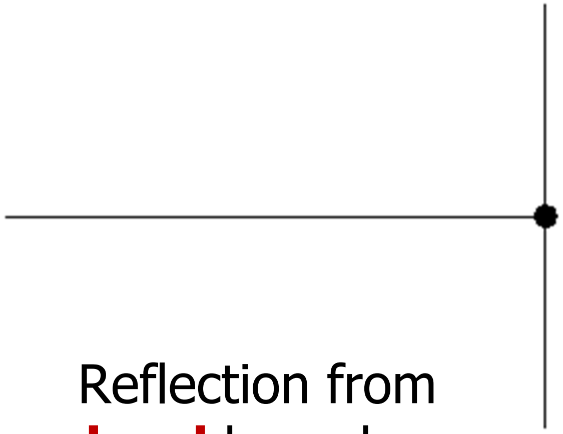
Motivation: Wave Pulse on a String

Motivation:
Wave Pulse on a String

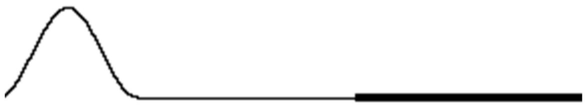
No termination



Reflection from **soft** boundary



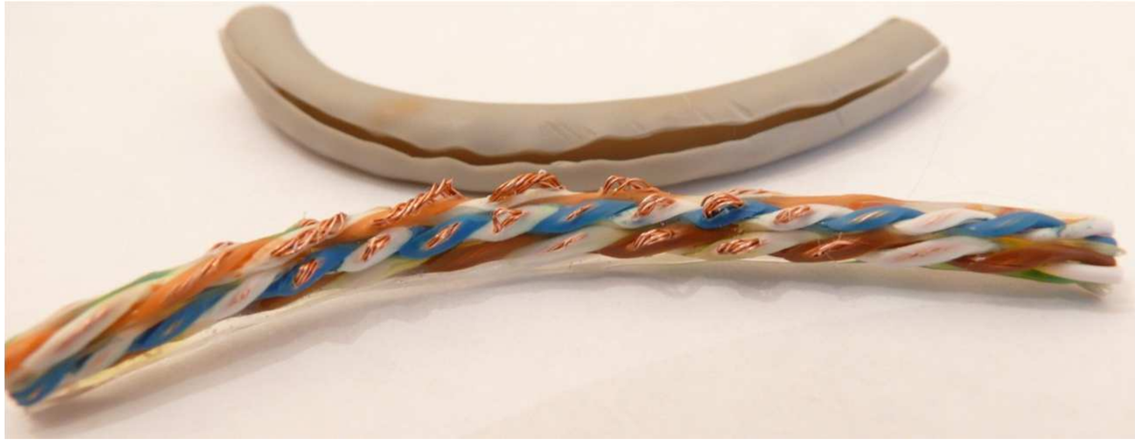
Reflection from **hard** boundary



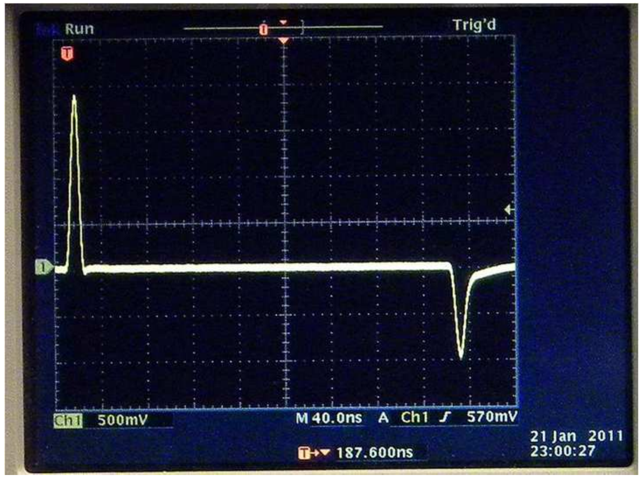
High to low speed (impedance)

Low to high speed (impedance)

TDR Examples

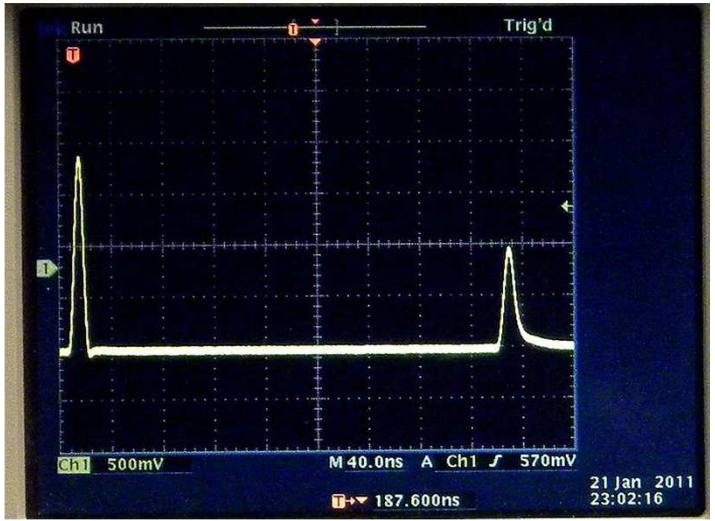


Melted cable (electrical short)



TDR: Inverted reflection

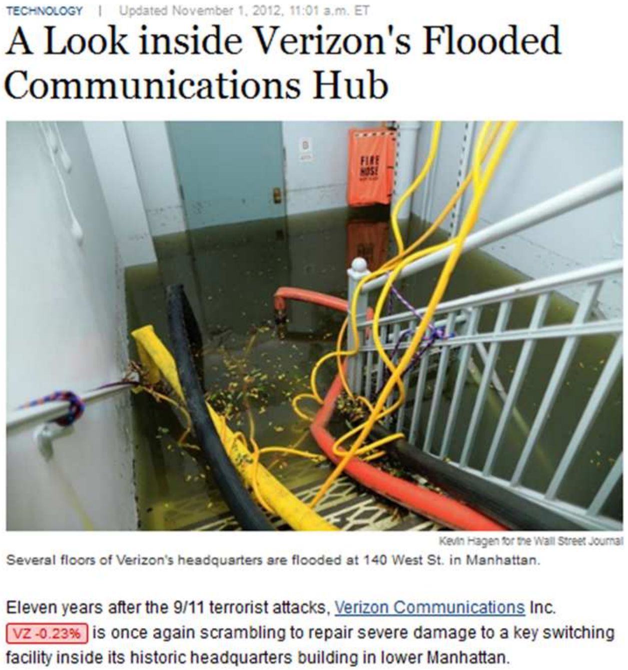
Cut cable (electrical open)



TDR: Reflection

TDR Example: Cable Moisture

Water-soaked/flooded cable



TECHNOLOGY | Updated November 1, 2012, 11:01 a.m. ET

A Look inside Verizon's Flooded Communications Hub

Kevin Hagen for the Wall Street Journal

Several floors of Verizon's headquarters are flooded at 140 West St. in Manhattan.

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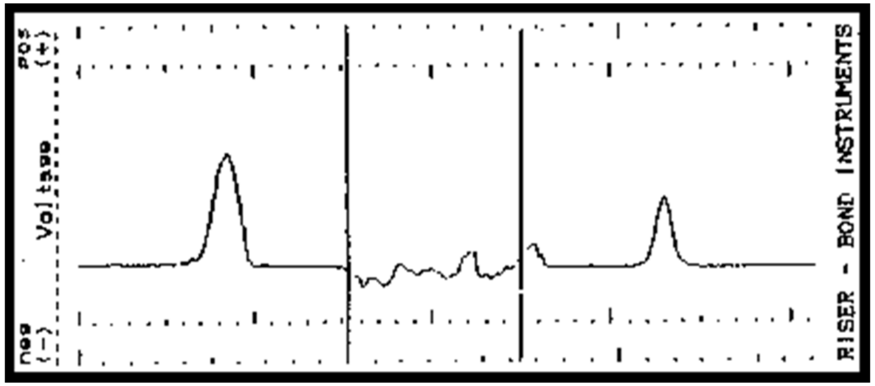
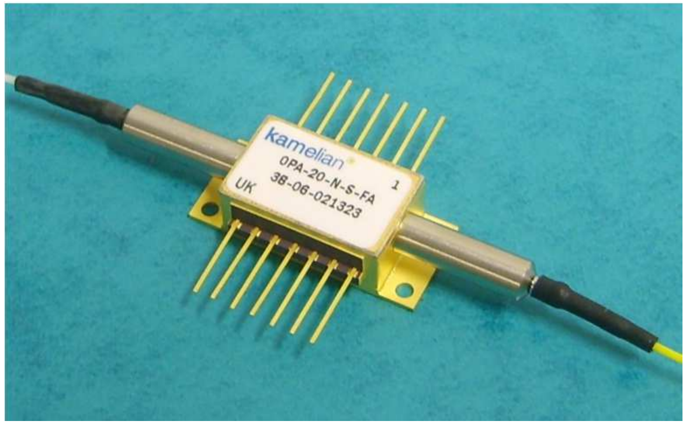
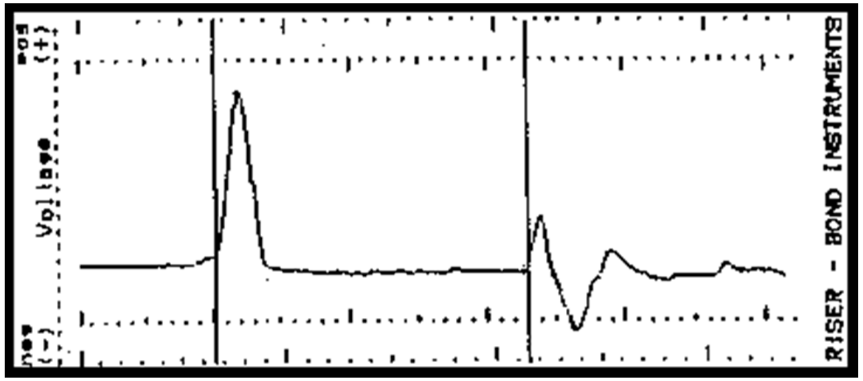
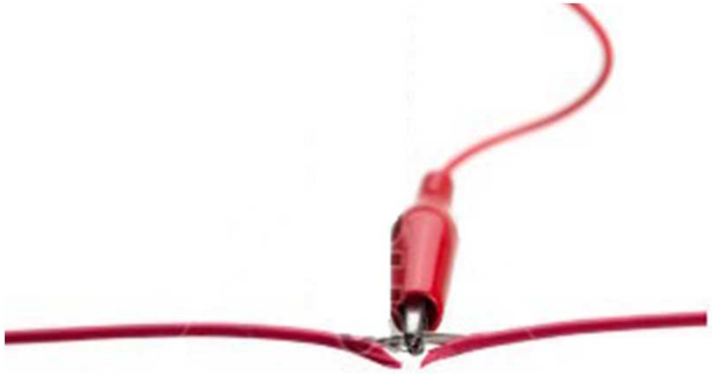


TDR Examples

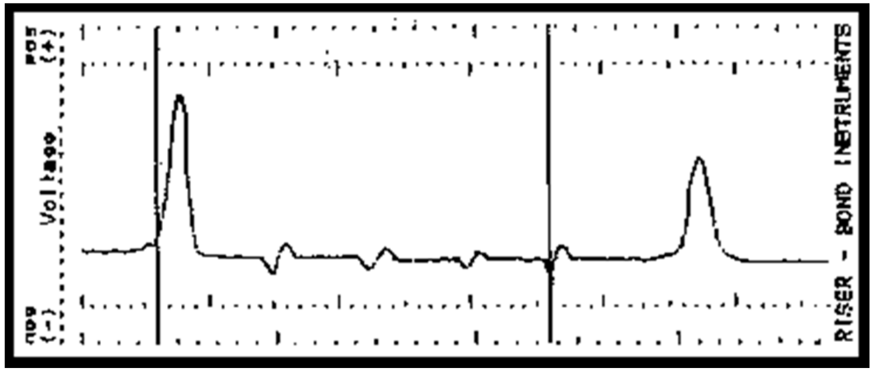


Faulty Amplifier





Wire Tap

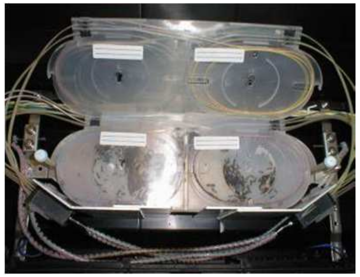


Protection against wildlife

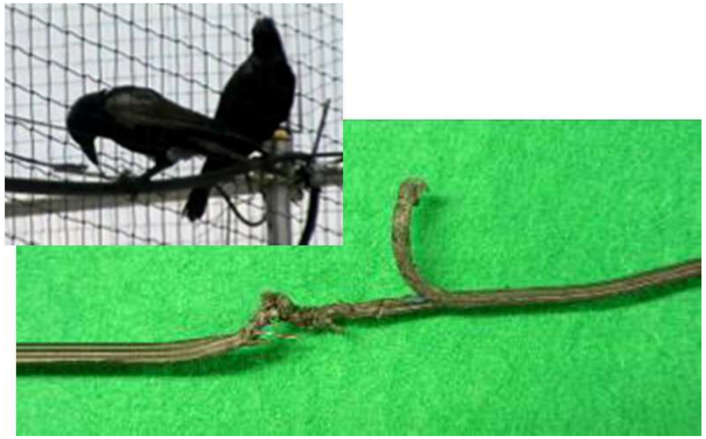
Rodents

Moths

Cicadas

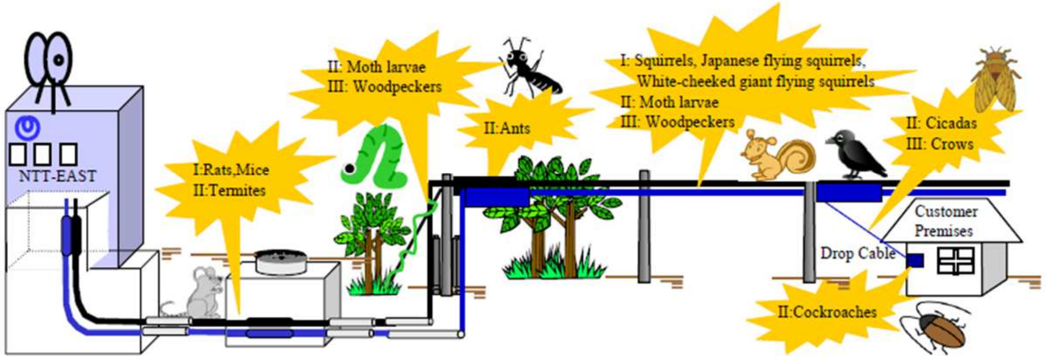


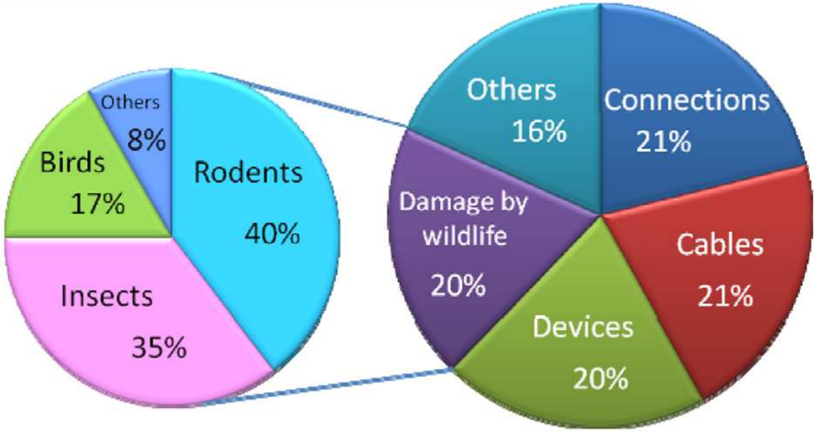
Ants



Crows

Protection against wildlife

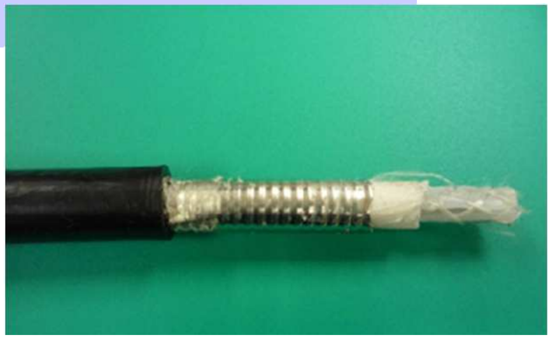


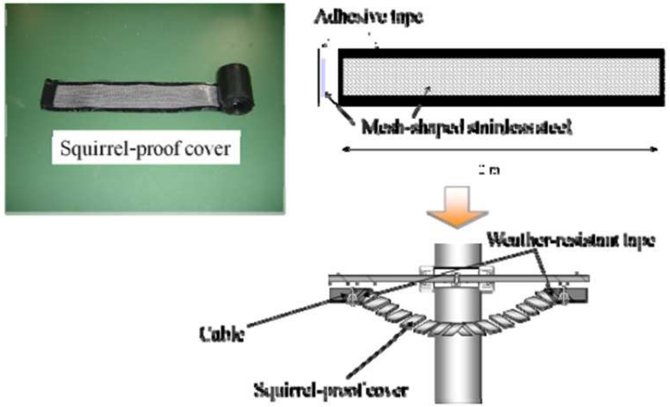


- Rodents (squirrels, rats, mice, gophers)
  - Chew on cables to grind foreteeth to maintain proper length
- Insects (cicadas, ants, roaches, moths)
  - Mistake cable for plants, burrow into it for egg laying/larvae
  - Ants invade closures and chew cable and fiber
- Birds (crows, woodpeckers)
  - Mistake cable for twigs, used to build nests
- Underground cables affected mainly by rats/termites, aerial cables by rodents/moths, drop cables by crows, closures by ants

Countermeasures against wildlife

- Use High Strength Sheath cable
  - PVC wrapping stainless steel sheath
  - Performance studies on cable (gnathodynameter)
- Cable wrap
  - Squirrel-proof covers: stainless steel mesh surrounded by PVC sheet
- Fill in gaps and holes
  - Silicone adhesive
- Use bad-tasting cord
  - PVC infused with irritants
  - Capsaicin: ingredient in pepper spray, irritant
  - Denatonium benzoate: most known bitter compound

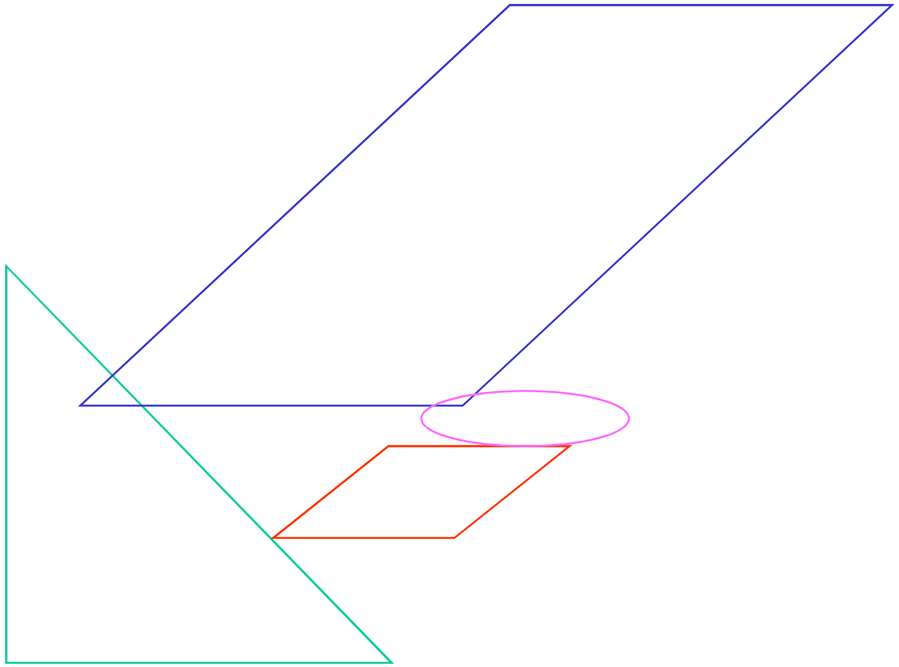




Security of Optical Networks

Why optical networks?

- Today’s long-haul networks are based on optical fiber
  - >50% of Internet traffic goes over fiber optics, and increasing
  - Optical is the best choice for high datarate, long-distance

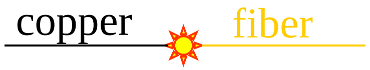


Why is fiber better?

- Attenuation per unit length
  - Reasons for energy loss
    - copper: resistance, skin effect, radiation, coupling
    - fiber: internal scattering, imperfect total internal reflection
  - So fiber beats coax by about 2 orders of magnitude
    - e.g. 10 dB/km for thin coax at 50MHz, 0.15 dB/km l =1550nm fiber
- Noise ingress and cross-talk
  - Copper couples to all nearby conductors
  - No similar ingress mechanism for fiber
- Ground-potential, galvanic isolation, lightning protection
  - Copper can be hard to handle and dangerous
  - No concerns for fiber

Why *not* fiber?

- Fiber beats all other technologies for speed and reach
- But fiber has its own problems
  - Harder to splice, repair, and need to handle carefully
- Regenerators and even amplifiers are problematic
  - More expensive to deploy than for copper
- Digital processing requires electronics
  - So need to convert back to electronics
  - Conversion is done with an optical transceiver
  - Optical transceivers are expensive
- Switching easier with electronics (but possible with photonics)
  - So pure fiber networks are topologically limited:
    - point-to-point
    - rings

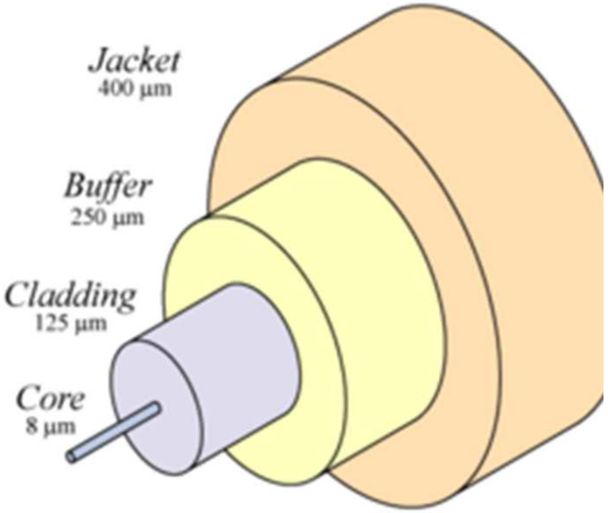


Main components of a fiber-optic network

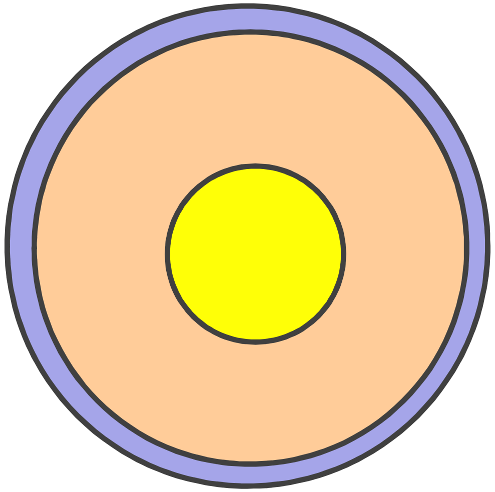
- Fiber
- Light sources and receivers
- Amplifiers
- Couplers
- Modulator
- Multiplexor
- Switch

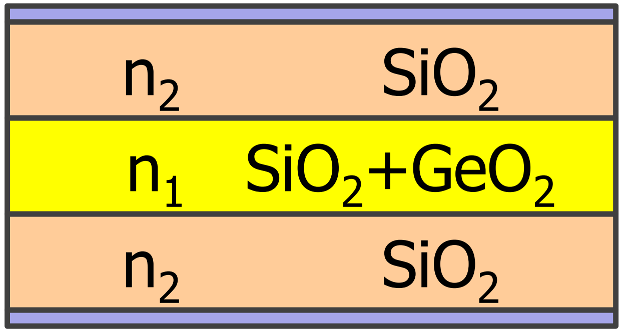
Optical Fibers

- Very pure and transparent silica glass
  - Jacket/buffer protects the rest of the fiber
- Core transmits light
  - Some fibers also use cladding to transmit light
- Cladding and core transmit light
  - Cladding has lower refractive index than core
  - Cladding causes light to be confined to the core of the fiber due to total internal reflection at the boundry between the two
    - Beyond critical angle, all light is reflected
  - Some fibers support cladding modes where light propagates in the cladding as well
    - Most fibers coat cladding with polymer with slightly higher refractive index, to rapidly attenuate light propagating in cladding
    - Exception: double-clad fiber, which supports a mode in both its cladding and its core



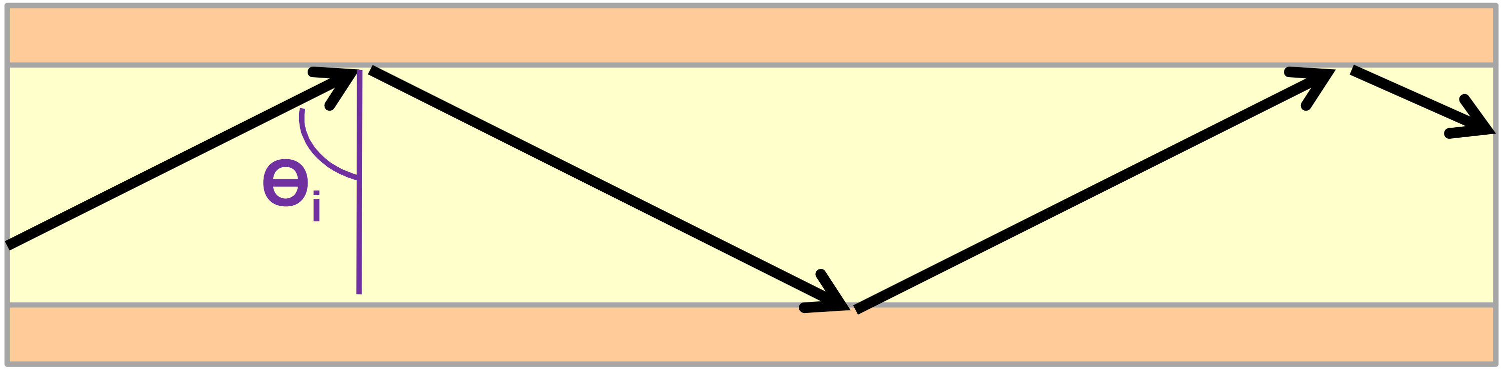
Inside an optical fiber



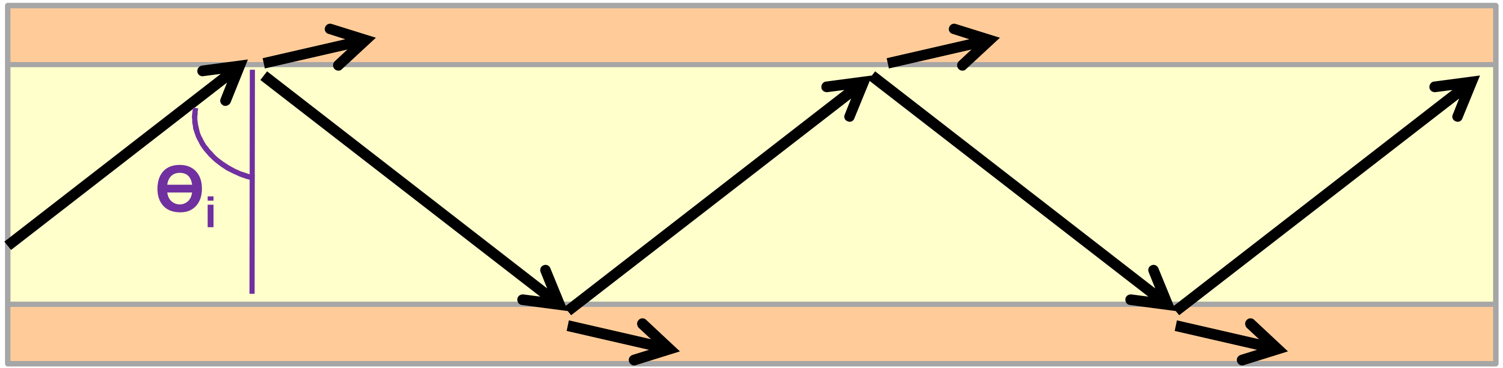


- Refractive index of core (n1) is bigger than that of the cladding (n2)
  - – Done by doping core with impurity (eg Germanium Oxide)
  - – Goal: cause light to be confined to the core due to total internal reflection

Keeping the light in the core with Total Internal Reflection

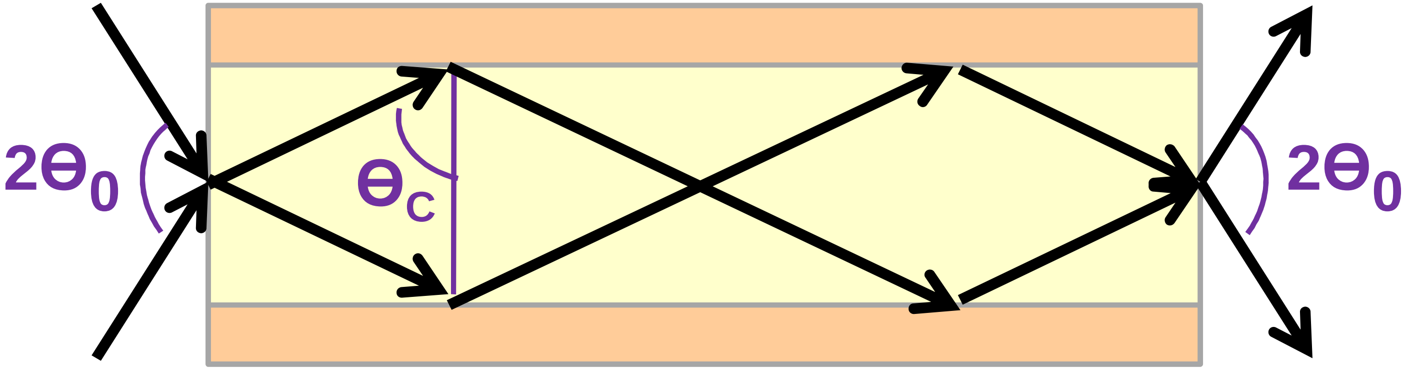


- Case 1: angle of incidence is less than the critical angle
  - $\Theta_i < \Theta_c$ $\Theta_c = \sin^{-1}(n_2/n_1)$ → All light is reflected
  - This really is 100% reflection – wouldn't have such low-loss fibers otherwise



- Case 2: angle of incidence is greater than the critical angle
  - $\Theta_i > \Theta_c$ → Some light is reflected, but some is also refracted

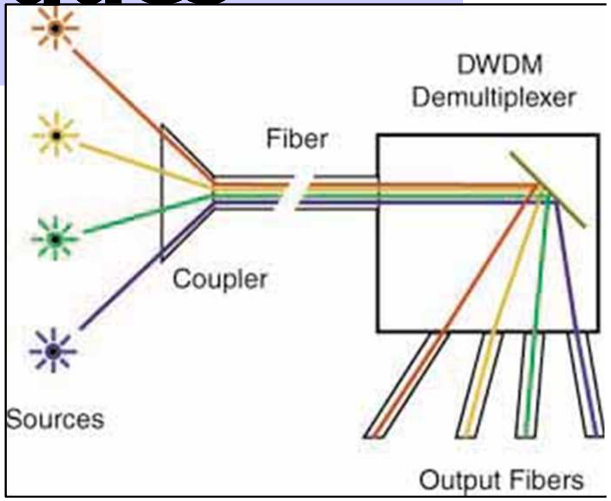
Acceptance angle

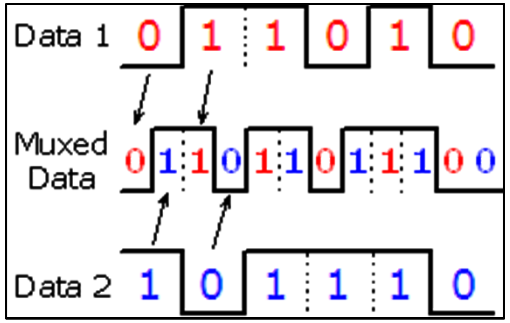


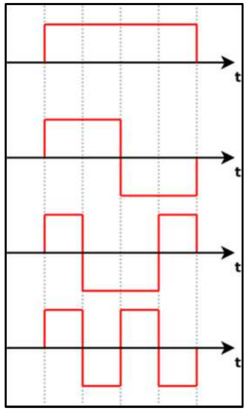
- Critical angle determines acceptance angle of light going in
  - Light received at too much of an angle will have high attenuation
  - Numerical aperture (NA): size of cone of light input that will be totally internally reflected
    - NA = n_0 sin (Θ_0)

Multiplexing Techniques

- Wavelength Division Multiplexing (WDM)
  - Different sources = different colors
- Optical Time Division Multiplexing (OTDM)
  - Different sources = different time slots
- Optical Code Division Multiplexing (OCDM)
  - Derive a set of orthogonal “codes”
  - Different sources = different codes

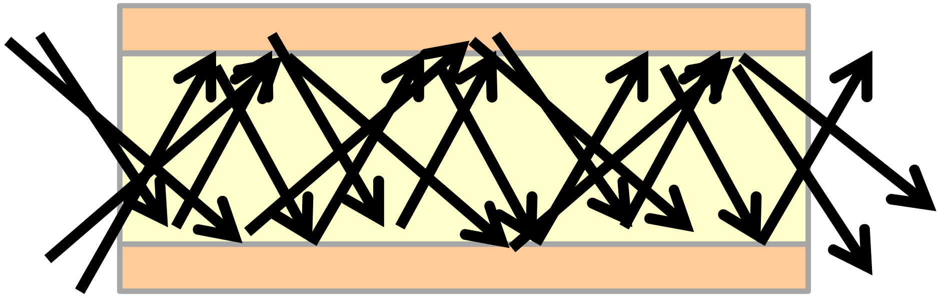




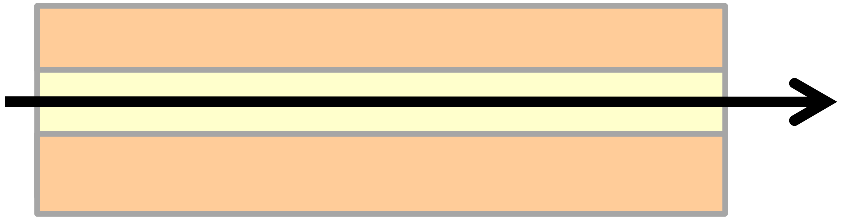


Single- vs. Multi-mode optical fiber

- Single-mode fiber is designed to carry a single “ray” (mode) of light
- Multi-mode fiber carries multiple rays/modes
  - Larger core than single mode
  - Higher loss, hence used over shorter distances (within a building or on a campus)
  - Typical rates of 10Mbit/s to 10Gbit/s of lengths up to 600 meters



Multi-mode



Single-mode

Signal attenuation in optical fibers

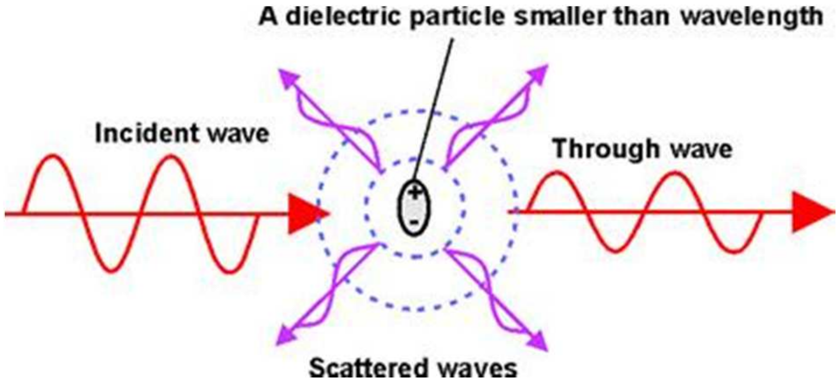
- Fibers are much more efficient transmitters than copper wires
- Certain wavelengths have especially low loss
  - 1300 and 1500 µm → 0.1 dB/km (~2% per km loss) → very efficient
  - Very efficient due to total internal reflection
- Why is there any loss at all?
  - Why are certain wavelengths more affected by loss?

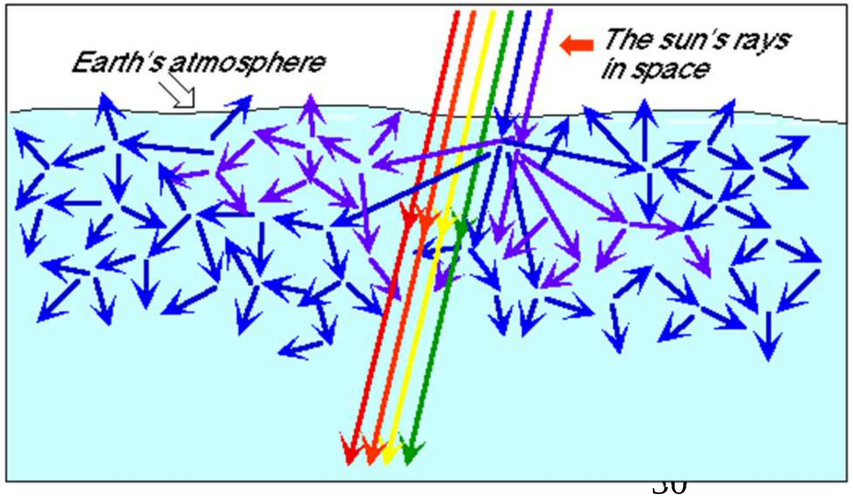
Why is there loss in optical fibers?

- Rayleigh scattering
- Material absorption
- Micro- and Macrobending
- Chromatic dispersion

Why is there loss in optical fibers?

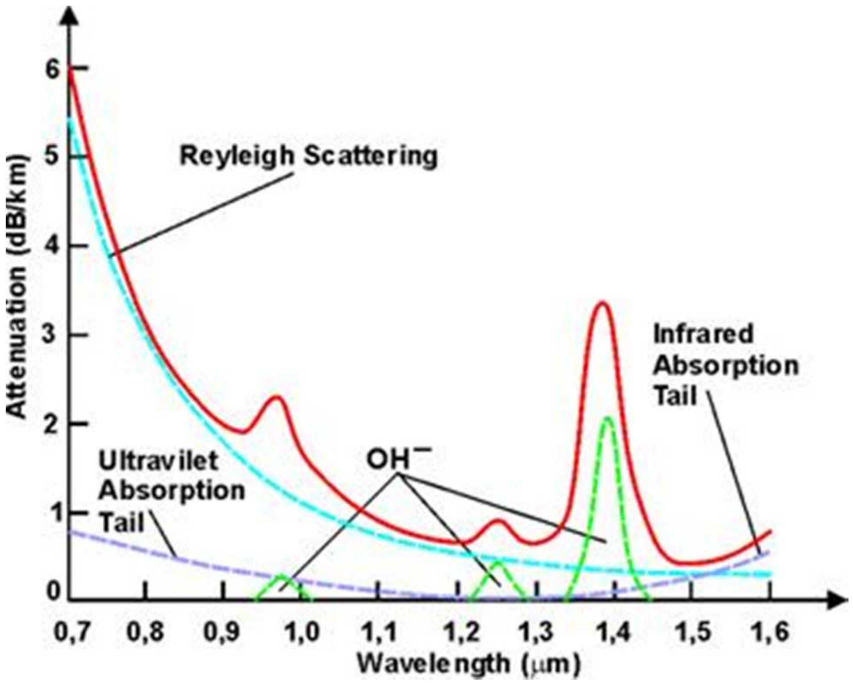
- Rayleigh scattering
  - Light hits and bounces off particles (individual atoms or molecules)
  - Blue is scattered more than other colors, as it travels in smaller, shorter waves
  - Same reason sky is blue during day and red at night
  - Bigger effect at smaller wavelengths





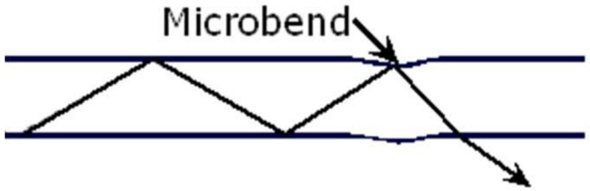
Why is there loss in optical fibers?

- Material absorption
  - Intrinsic absorption in infrared and ultraviolet bands
  - Impurities in optical fibers
    - Most important one: water in the form of hydroxyl ions, causing losses at 950, 1250, and 1380 nm

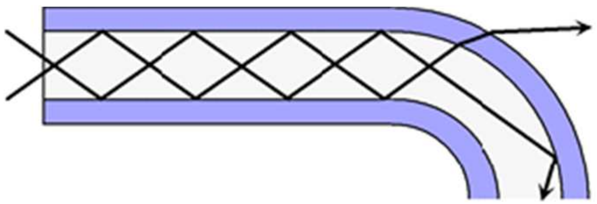


Why is there loss in optical fibers?

- Mechanical issues
  - Microbending: Local distortions of fiber geometry/refractive index
  - Macrobending: excessive fiber curvature
    - Occurs when installing fiber



Microbending



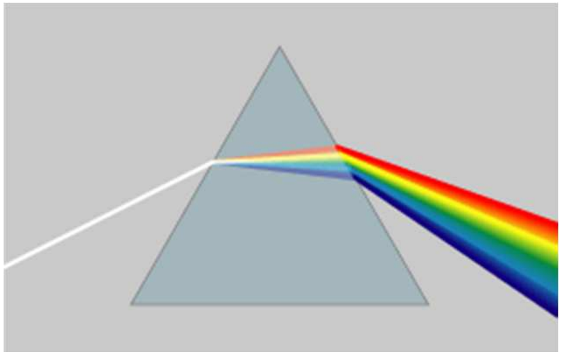
Macrobending

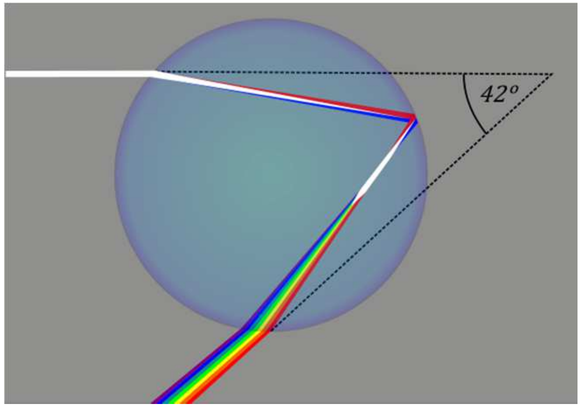
Macrobending example

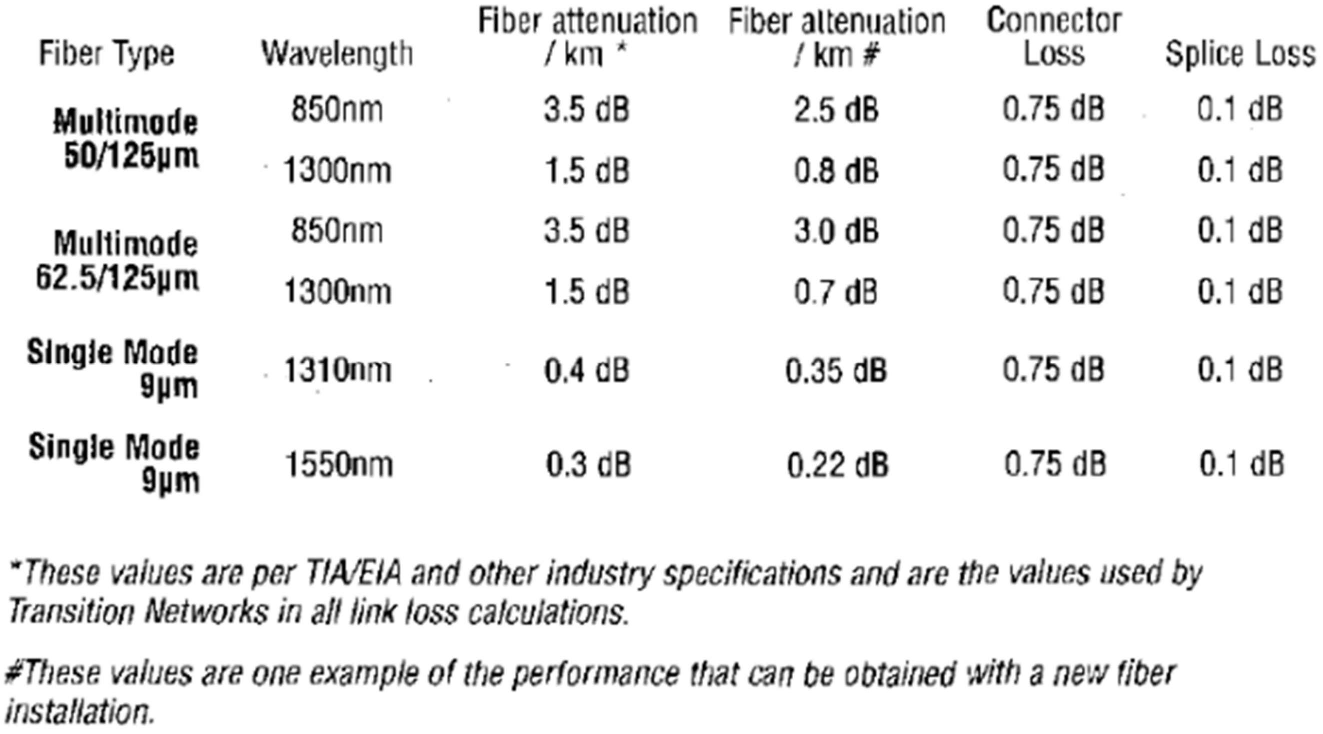
- http://www.youtube.com/watch?v=1ex7uTQf4bQ

Chromatic dispersion

- Velocity of light is 3x10^8 m/s in vacuum
  - But in a transparent medium, phase velocity of light wave depends on its frequency
  - Red, which has longer wavelength than blue, will travel faster
  - In glass, red travels at 66.2% of c, blue travels at 65.4% of c
    - This is what causes rainbows







Fiber Type	Wavelength	Fiber attenuation / km *	Fiber attenuation / km #	Connector Loss	Splice Loss
Multimode 50/125µm	850nm	3.5 dB	2.5 dB	0.75 dB	0.1 dB
	1300nm	1.5 dB	0.8 dB	0.75 dB	0.1 dB
Multimode 62.5/125µm	850nm	3.5 dB	3.0 dB	0.75 dB	0.1 dB
	1300nm	1.5 dB	0.7 dB	0.75 dB	0.1 dB
Single Mode 9µm	1310nm	0.4 dB	0.35 dB	0.75 dB	0.1 dB
Single Mode 9µm	1550nm	0.3 dB	0.22 dB	0.75 dB	0.1 dB

Notes:

***** *These values are per TIA/EIA and other industry specifications and are the values used by Transition Networks in all link loss calculations.*

*These values are one example of the performance that can be obtained with a new fiber installation.*

Laying Fiber

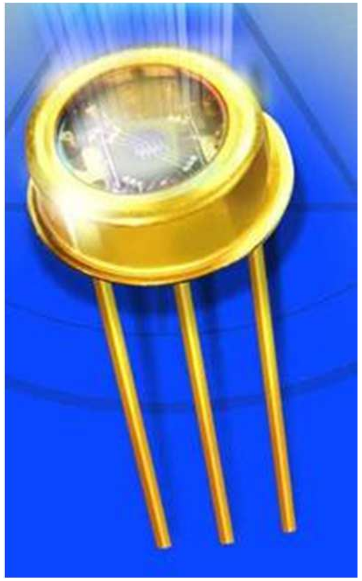
- How to lay cable over long distances?
  - Rail lines sell easements to permit laying of cable along rail line right-of-ways
  - Digging up and laying is the expensive part
    - So, lay extra fiber and leave it dark (“dark fiber”)
    - Light it up when more capacity needed

Optical components

- Transmitter/receiver
- Optical amplifier
- Optical coupler/splitter
- Optical delay units (packet buffering)

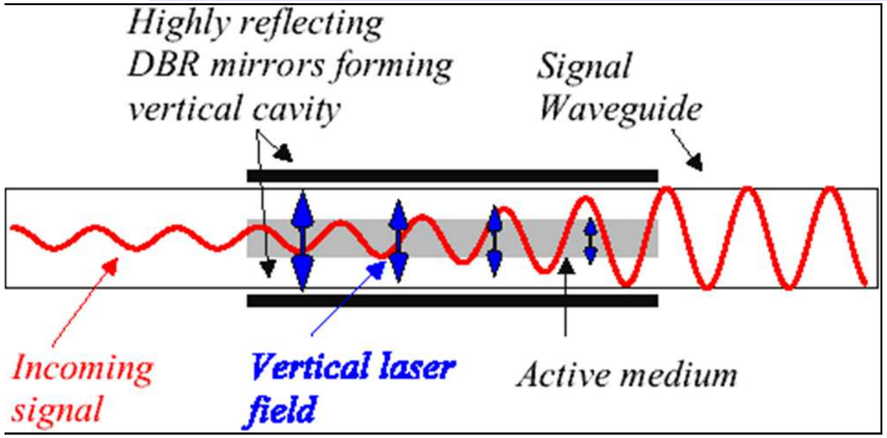
Optical transmitters/receivers

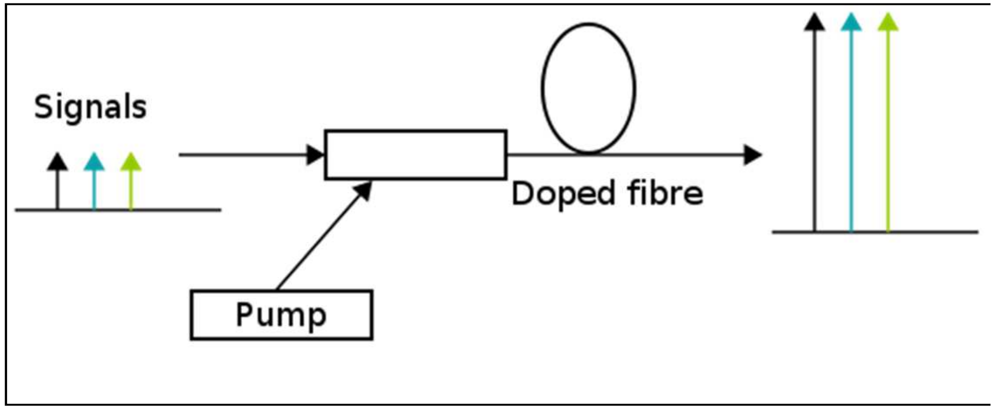
- Transmitting light with lasers
  - Laser diodes: created by doping thin layer on crystal wafer to create a p-n junction
  - Fiber Laser: Gain medium (doped optical fiber) amplifies beam through sponaneous emission



- Receiving light with photodetectors
  - Inverted diode: apply reverse voltage across p-n junction, light excites current

Optical Amplifiers





- Amplifies optical signal without converting it to electricity
- Doped Fiber Amplifier: signal is amplified through interaction with doping ions
- Used to correct attenuation
  - Placed every 100km on long-haul links

Optical Coupler/Splitter

- Splitter: The optical version of a copying machine
  - Divides one incoming signal into multiple signals
  - Made from half-silvered mirror, or two joined prisms
  - Adjusted so that half of light is reflected and other half is refracted
  - Coupler: joins two signals
- Uses:
  - Getting two copies of a signal (wiretapping)

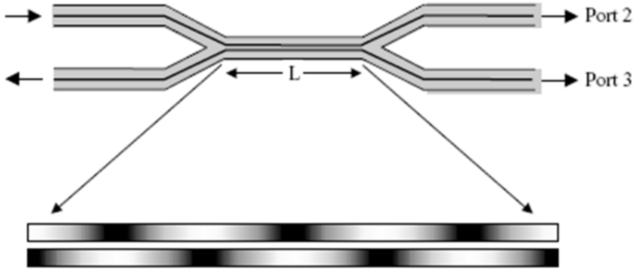
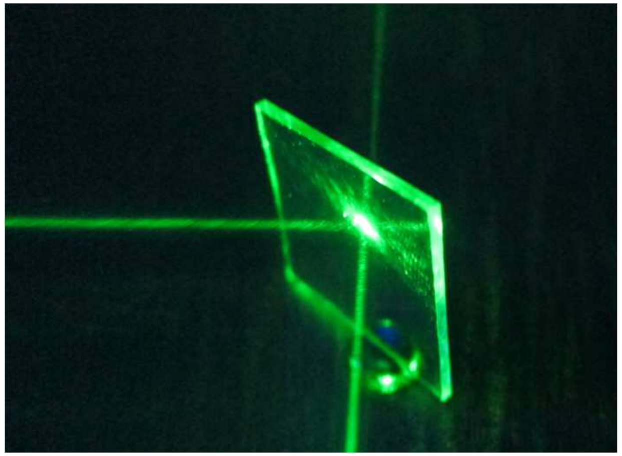
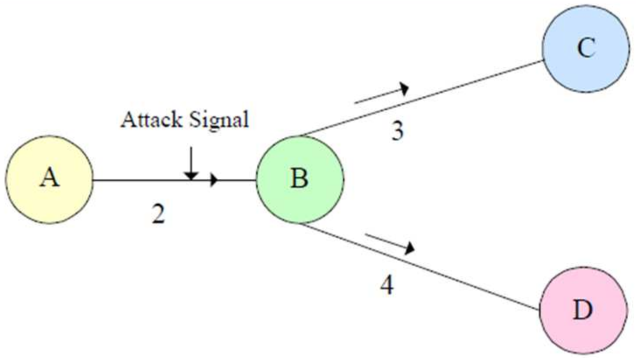


FIGURE 12.3 Directional coupler consisting of two fibers whose cores are brought close to each other. Due to interaction between the fibers, there is a periodic exchange of power between the two fibers, as shown in the lower part of the figure.



Optical Networks: Vulnerabilities and Countermeaures

Service Disruption Attacks



- Goal: cause delay, service denial, QoS degradation, spoofing
- Can easily cut/disrupt optical fiber
- Can bend fiber to radiate light in/out of fiber
- In-band Jamming
  - Attacker injects signal to confound receiver
  - Signals flow through nodes without electrical regeneration → attack can easily spread through network

Service Disruption Attacks

- Out-of-band jamming: attacker jams signal by exploiting leaky components
  - Exploits crosstalk in various components
- Examples
  - Attacker can hop wavelengths by sending very strong signal
    - WSSs can have crosstalk levels of -20dB to -30dB
  - Inject signal on different wavelength but within amplifier passband
    - Gain for comm signal is robbed by the attack signal
  - Electromagnetic Pulses (EMP) could cause both in-band and out-of-band jamming

Tapping Attacks

- Contemporary demultiplexers exhibit crosstalk levels of 0.03% to 1%
  - Leak a little bit of the signal on the wrong path, attacker can listen in
- Fibers can leak across wavelengths due to chromatic dispersion
- Optical amplifiers can leak due to gain competition
  - Attacker can co-propagate a signal on a fiber and observing cross-modulation effects
- Tapping can be combined with jamming
  - Tap, and inject a correlated signal downstream of the tap point
  - Very harmful to users with low SNR

Mitigating Attacks on Optical Networks

- Optical Limiting Amplifier: limits output power to specified maximum
  - Limiting light power limits crosstalk and service disruption attacks
- Band-Limiting Filters: discard signals outside a certain bandwidth
  - Can prevent gain competition in optical amplifiers

Mitigating Attacks on Optical Networks

- Physically strengthen or armor the cladding
  - Bury cable in concrete
  - Enclose cable in pressurized pipe
  - Usually very expensive
- Choose devices with lower crosstalk
- Choose more robust transmission schemes
  - Coding to protect against jamming
  - Intelligent limiting of signals to certain bandwidths/power constraints
- Architectural techniques
  - Avoid easily-compromised links for sensitive communications
  - Judicious wavelength assignment to separate trusted from non-trusted users

Detecting Attacks

- Power detection: compare received optical power to expected optical power
  - Too much: jamming attack?
  - Too little: tapping?
  - Challenges: slight changes are difficult to detect; small but detectable changes result from component aging and fiber repairs. Tuning problem.
  - Sporadic jamming might harm BER but might not change power levels enough to show up

Detecting Attacks

- Optical spectrum analysis: measure spectrum of optical signal
  - Can help localize gain competition attacks
  - Require additional processing time and hence can slow detection time
- Pilot tone: known signal, different carrier frequency, but traveling on same path as data
  - Used to detect transmission disruption

Detecting Attacks

- Optical TDR: like pilot tones, but analyze echo
  - Used to detect attacks involving fiber tampering, e.g. in-line eavesdropping
  - Challenge: EDFAs are sometimes unidirectional, not reflecting the echo
    - May require bi-directional amplification