Waveguide modes for Terabit transmission on ordinary wiring

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plasmon polaritons
Couirtesy: Bilkent U

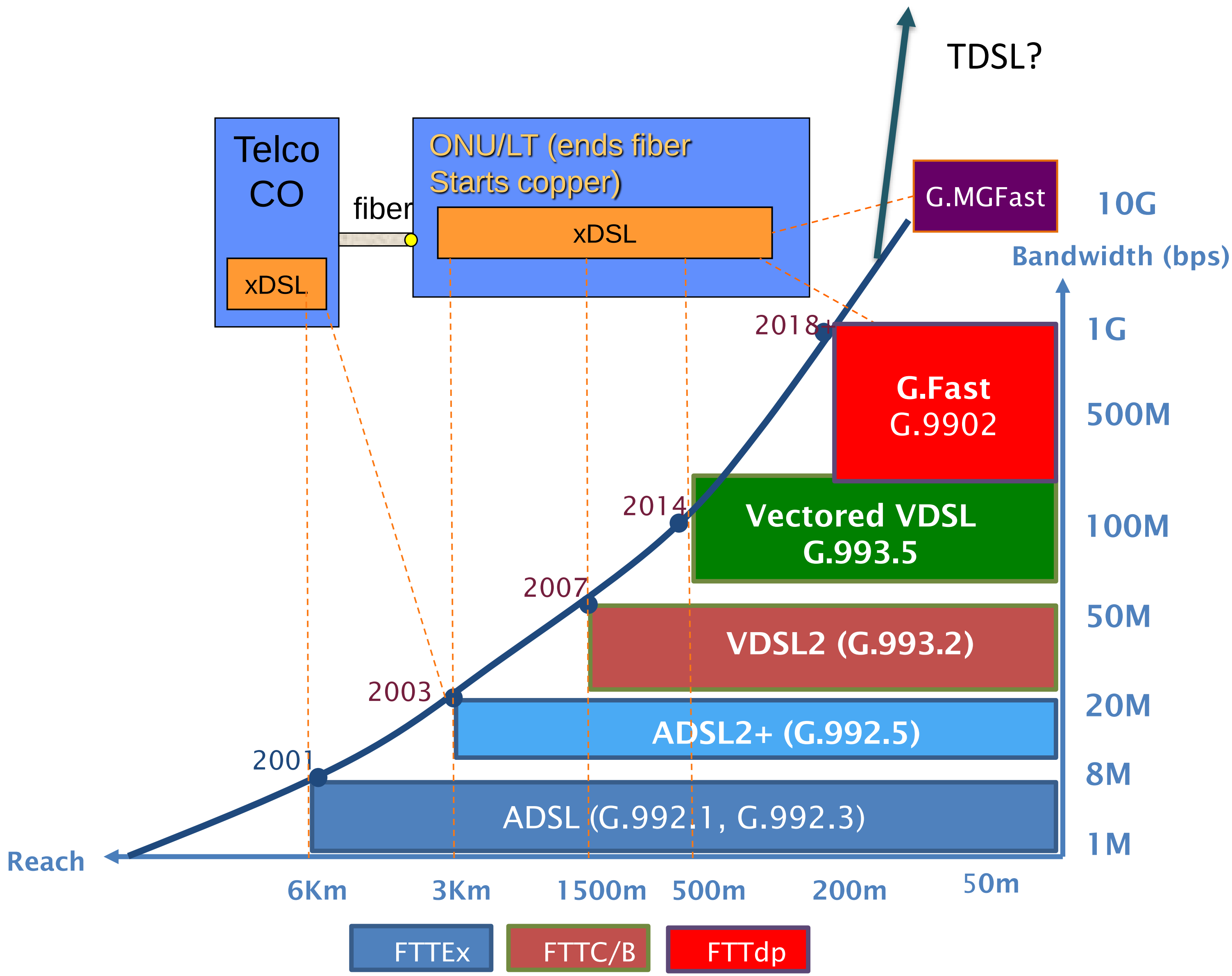
Drivers for Higher-Speed DSLs

- MULTITUDE of 5G smaller cells
  - high-speed low-latency wired support
  - New 5G-fiber cost = 400B euros (for europe, DT CTO, 2016)
- Fiber theoretical capacity ~ 500 Tbps
  - Today supports 1 Gbps to 100 Gbps (access-network)
- **BUT**
  - FTTP install costs $2000-$3000/home (average)
- The copper twisted pairs are there (1.3B)
  - Run fiber part of the way ($3000/10 homes is a better business case)
  - Continues x in xDSL, so can x=T?

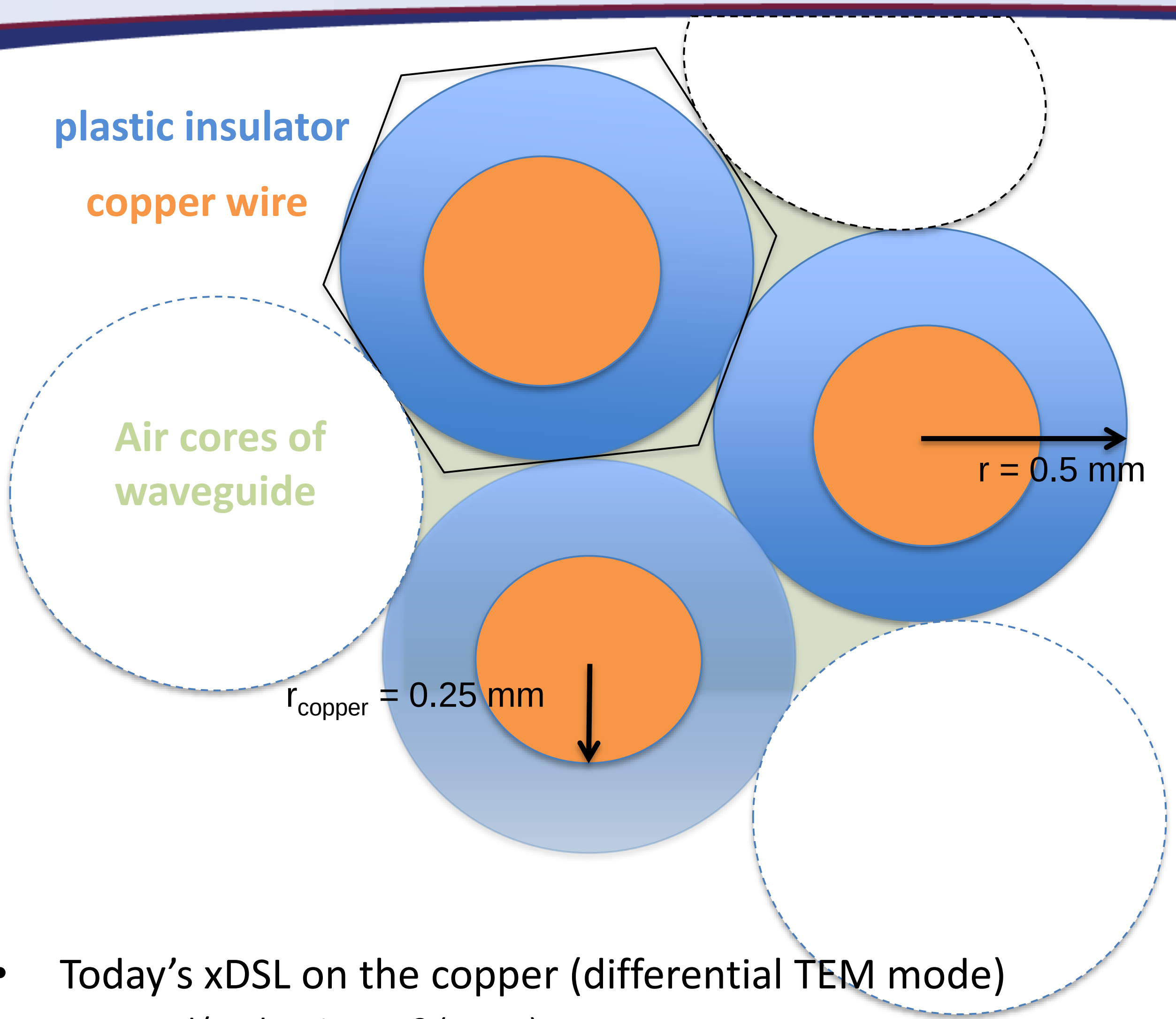
Yes, we think so

Ovum 2015

Current xDSL progression



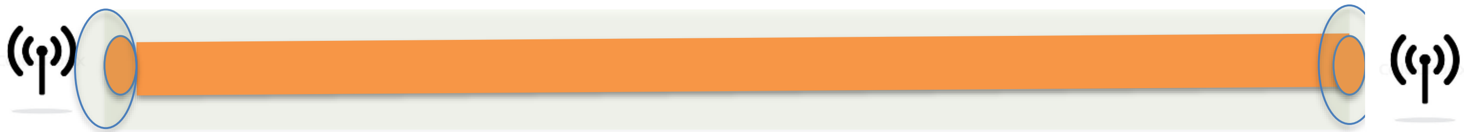
Single Pair: Cable Cross Section



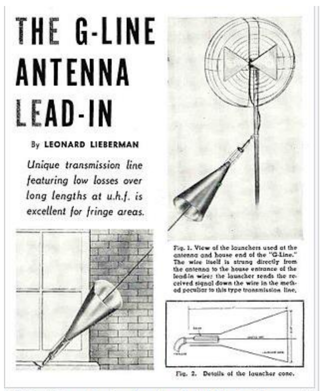
- Today's xDSL on the copper (differential TEM mode)
  - And/or the air gaps? (green)

Surface Wave Transmission

(1909 Sommerfeld wave)



- Surface Mode (or TM10)
  - Waves use single wire in TM mode as guide
    - E.g. Goubau antenna or “G-line”
    - See also AT&T “AirGig”
  - Effectively wireless transmission
    - Works reasonably well (no atmosphere inside cable)
    - Dielectric (plastic) can help (see [Wiltske]), p. 971) keep energy close
  - Tube with non-uniform dilectric constant
    - Conformal mapping of 1/r dimension
- Energy still leaks off wire if bent



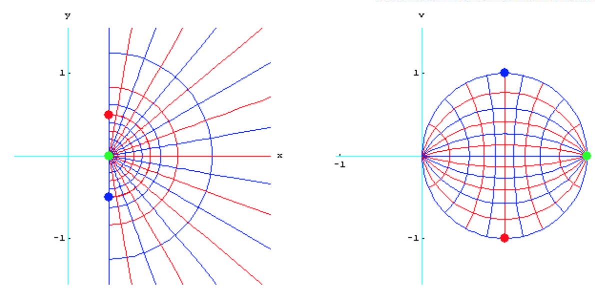
THE G-LINE ANTENNA LEAD-IN

By LEONARD LIEBERMAN

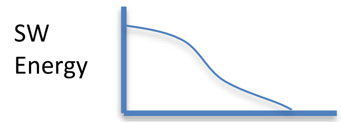
Unique transmission line featuring low losses over long lengths at u.h.f. is excellent for fringe areas.

Fig. 1. View of the launchers used at the antenna and house end of the "G-Line." The wire itself is strung directly from the antenna to the house entrance of the lead-in wire; the launcher sends the received signal down the wire in the method peculiar to this type transmission line.

Fig. 2. Details of the launcher cone.



Mathfaculty.com



Surface-Wave Measurements 2006

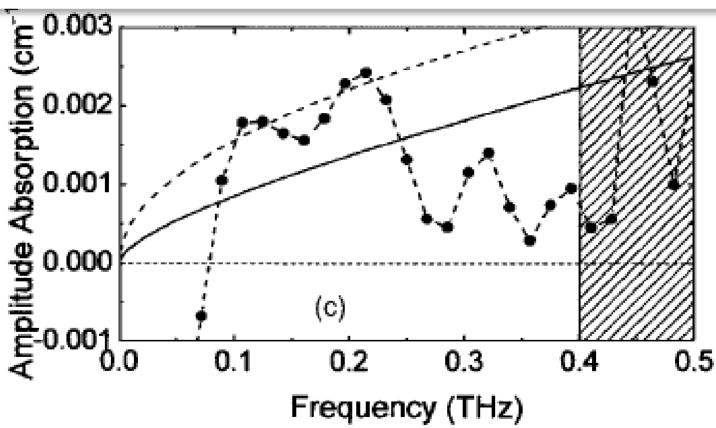
- Single wire TM01
  - Wiltse's surface-wave measurements are 2mm wire core, not 0.5mm)
  - Measures attenuation/m
- Wiltse Extrapolation
  - .8 dB/m @ .1-.3 THz
  - Fatter wires
- Grischkowsky has .5 db/m
  - For .52mm diameter Cu wire
  - 2nd wire would probably improve transfer
  - Like in twisted pair
- 100m should see 50-80 dB
- Bending is less of a problem
  - Each wire has a TM mode
  - Between wires is a TEM plasmon polariton mode
  - 2nd TEM "plasmonic" (weaker?) to other pairs – somewhat like phantoms/split-pairs
  - TIR mode
  - Surface mode (maybe same as TM …)
  - 3 -- 4 modes per pair

Wiltse

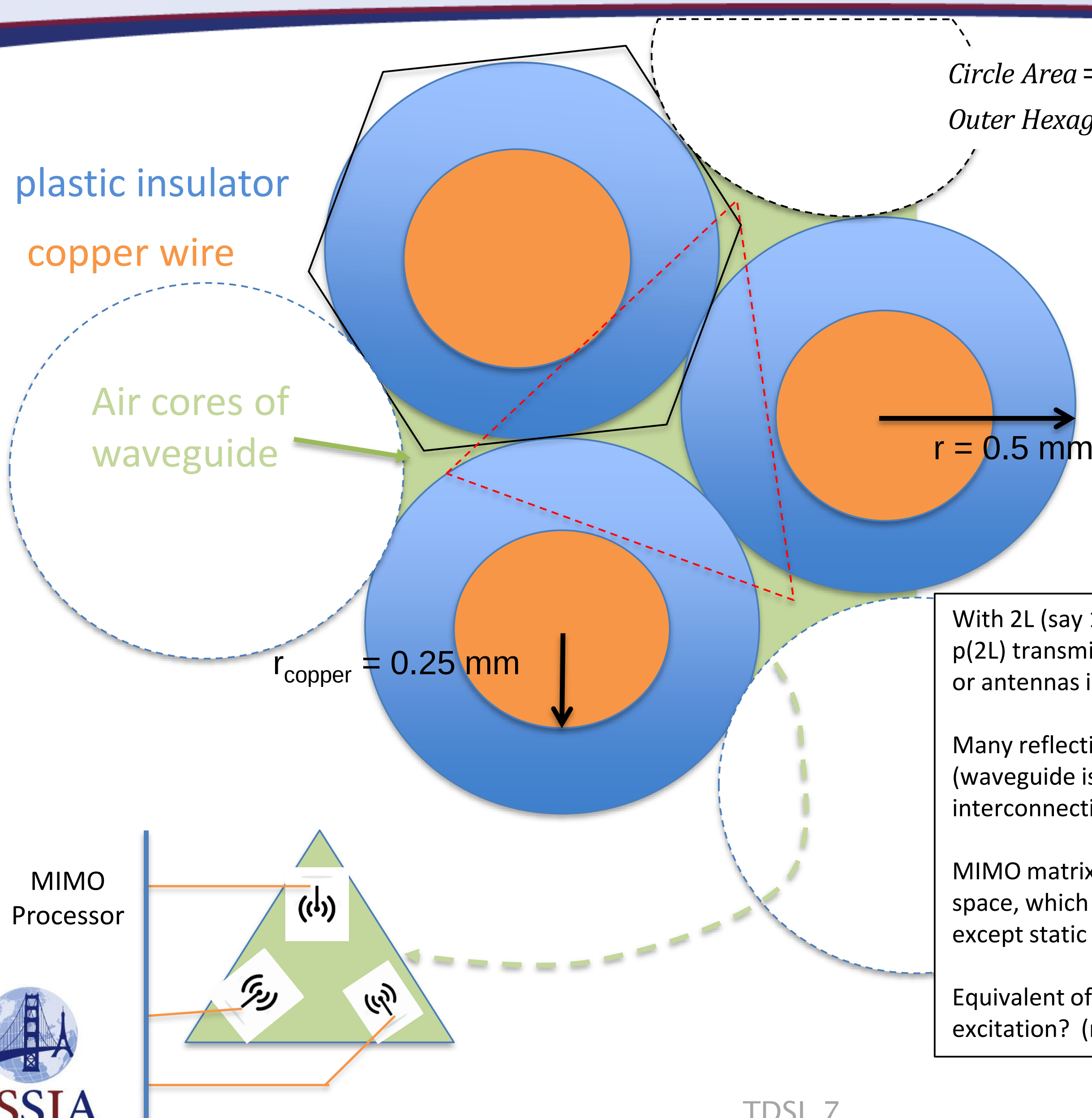
Table II
Attenuation of Single-wire Transmission Lines

Wire Diameter mm	Frequency GHz	Calculated Attenuation dB/m	Measured Attenuation dB/m
2.032	105	0.23	0.46
3.251	105	0.16	0.33

Grischkowsky



Cross Section Geometry



$Circle\ Area = pr^2$

$Outer\ Hexagon = \frac{6}{\sqrt{3}} r^2$

$difference = .32r^2$

3/6 difference is area of the free-space in a triangular "waveguide" = *.16r*^{2}

Altitude of triangular "waveguide" = .53*r*

(600 GHz is λ/2)

If plastic used 200 GHz

With 2L (say 100+) wires, there can be p(2L) transmitters (m=0,1,…) or antennas into waveguide gaps (triangles)

Many reflections to any spatial point: (waveguide is really "Swiss Cheese" with many interconnecting spaces). Big MIMO opportunity.

MIMO matrix with Gaussian entries at any point in space, which is same as Rayleigh fading in wireless, except static sample

Equivalent of "tunable" laser with vector-coordinated excitation? (much less attenuation – like fiber?)

Vectoring = Massive MIMO

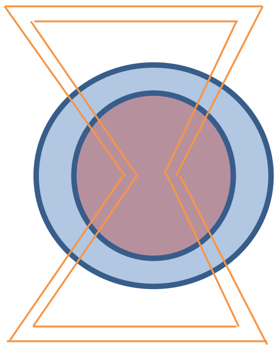
- Lets try m=1 with TM antenna(s) wirelessly exciting each wire end
  - Photoconductive antennas perhaps?
  - Both polarizations (TM and TE) for each wire
    - Or possibly for pairs of wires

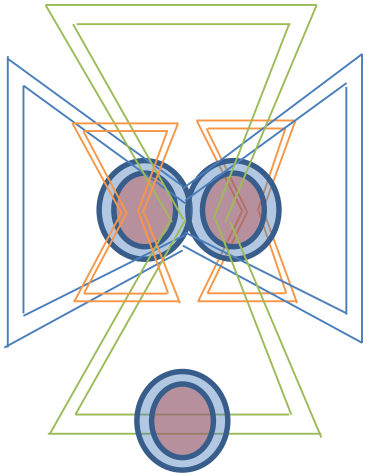
- There is also a TEM plasmon polariton mode
  - At least one, really two
  - Could think of this as dual polarization, but not quite really
  - There is also at least one TIR mode (total internal reflection) with sheath

- Nominally intersections would introduce crosstalk between the TMs and TEMs
  - Use MIMO or MISO (just like in mmW wireless 5G, except mmW/10)
  - Will tend toward log normal

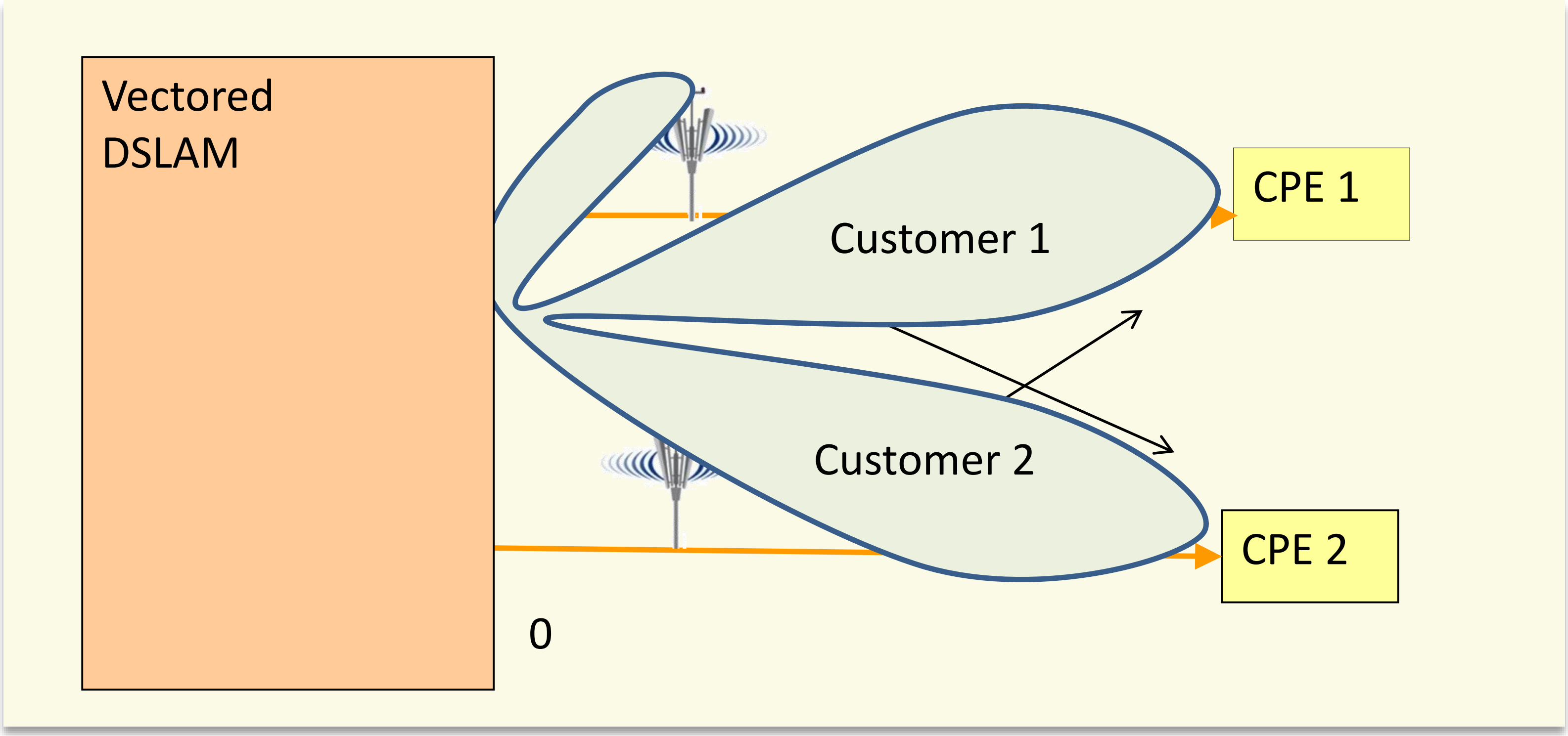
- "Swiss Cheese" Waveguide
  - ULTRA rich scattering (exactly what massive MIMO needs)

- Coupling (splicing) is open to innovations, but photoconductive and other types of antennas/lasers/detectors do exist in these frequency ranges today.





Vectoring ~ Channel Hardening



- Say from 100 GHz to 300 GHz
  - Use 4096 tones, so roughly 50 MHz wide each
  - Two wires in a pair, and two polarizations
- Its conceivable that even 2.5 bits/ tone average, so 1 Tbps

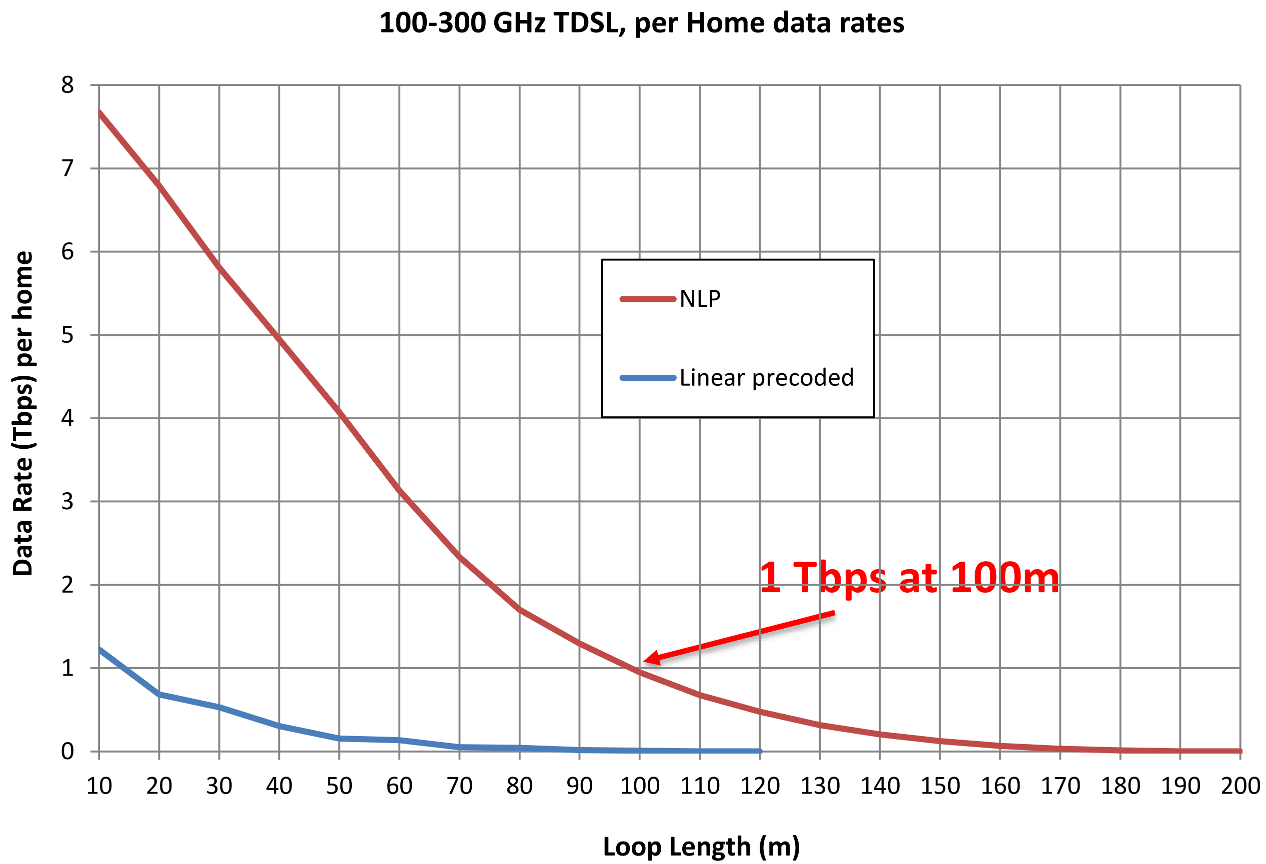
Model

- Channel (Grischkowsky) $$H(f) = e^{-0.05 \cdot \left(\frac{f}{10^{11}}\right) \cdot d}$$
- Xtalk (this paper) $$X(f) = 10^{k/10} \cdot e^{-0.05 \cdot \left(\frac{f}{10^{11}}\right) \cdot d}$$
  - Log normal

Mean k=0 dB
Std. Dev. = 6 dB

- 20 dBm total transmit power, flat transmit PSD
- 4096 subcarriers from 100 GHz to 300 GHz, 48.8 MHz subcarrier spacing
  - Bit loading from 1 to 12 bits/Hz
  - 10% phy-layer overhead removed before presenting results
  - 6.0 dB coding gain, 1.5 dB implementation loss
  - Carriers from 50 GHz to 150 GHz were used for the 10 Gbps results
- 50 pairs, vector precoded with either zero-forcing linear precoder or Non-Linear Precoder (NLP) using Generalized Decision Feedback Equalization (GDFE); ideal channel estimation assumed.
- -160 dBm/Hz background AWGN.
- We also add in a TM2 and TEM2 mode for 400 GHz to 500 GHz (same parameters)

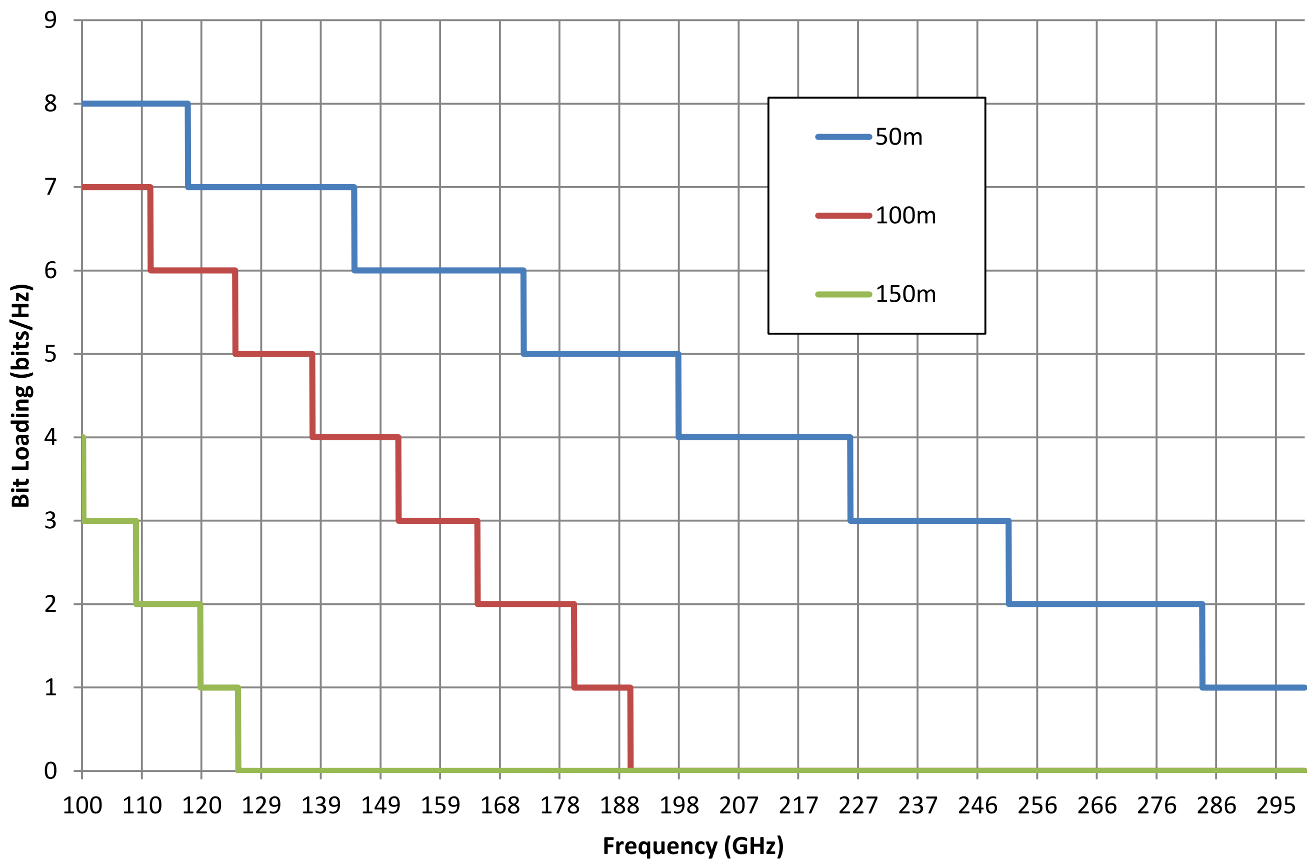
Results in Tbps [down+up]/pair



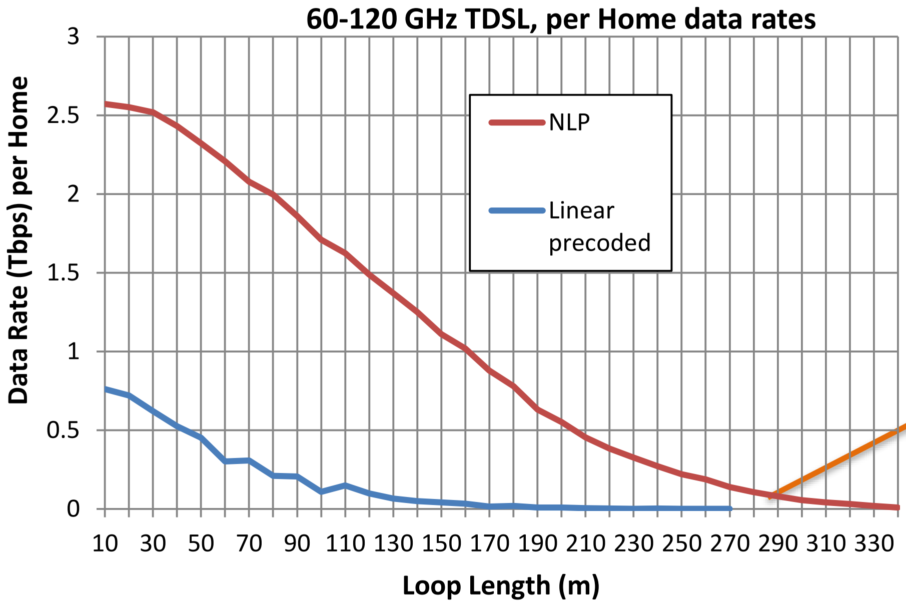
- Can any PON get 1 Tbps to each customer?

Bit Loading

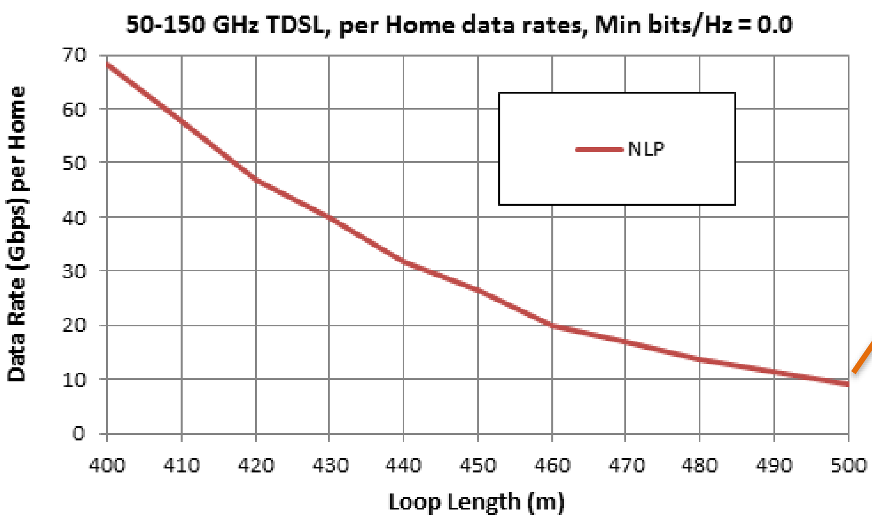
(each polarization of 1 wire)



Longer Range, Lower Speed?



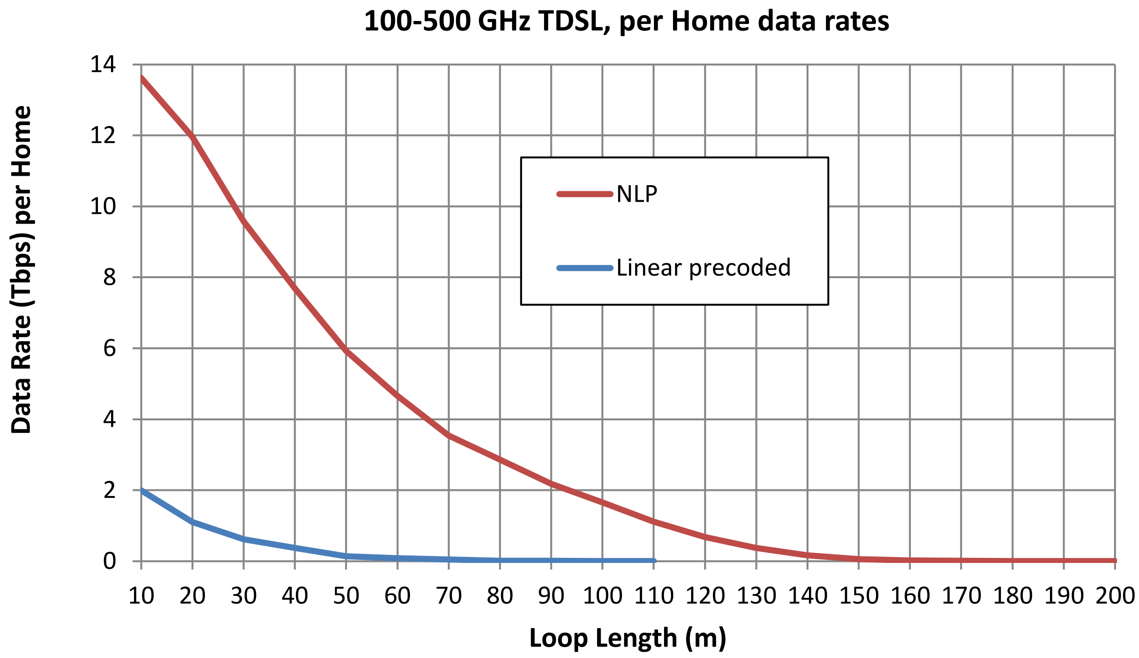
100 Gbps > 300m



10 Gbps > 500m (~0.5km)

Very-high speed TDSL

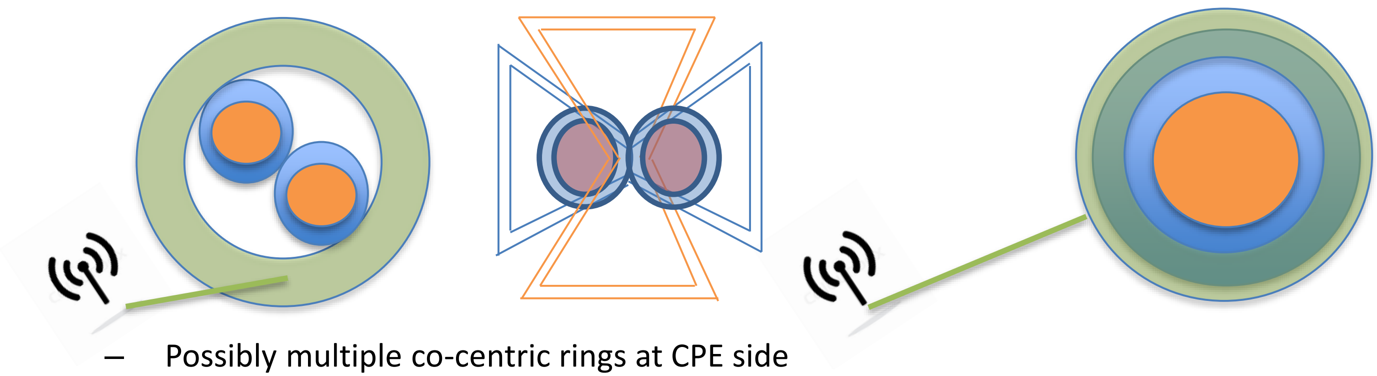
- Adding TE2 and TEM2 modes from 400-500 GHz



100 meters	300 meters	500 meters
2 Tbps	100 Gbps	10 Gbps

Antennas (analog processing)?

- What would antennas look like ?
  - Annular rings around each wire end
  - Also at CPE side



  - Possibly multiple co-centric rings at CPE side
  - Combinations
  - Catch as much drifting energy on CPE receiver as possible (dual for upstream transmitter)

- What would coupling to waveguides look like? (photoconductive, photodetect)
  - It may be feasible to have on die a coupler in this 200-400 GHz frequency range.
    - Coupling losses?

- Have not included "nested MIMO" over the 4 (or more) antennas per home in results
  - This will be a large improvement (like vector-bonding in multi-line DSL, but perhaps better)
    - Current plots ignore this improvement
  - However, we were optimistic on the energy loss after the sheath-break on the surface waves
  - The two effects may offset

Digital Signal Processing?

- Conversion devices?
  - Might not use all 200 GHz, but still …
  - ADC’s running at 120 Gsamples/second exist (Jarittech)
  - Use Multicarrier (AMT instead of DMT)?
    - Each tone could have its own ADC/DAC (so easily available, but many in parallel)
- Processing Capabilities
  - Vector Engine, even at per tone of 50 MHz
  - .1-.25 Giga-ops per tone
  - Tera-ops for a full system
    - Current Nvidia Tesla GP100 has 5 Teraflops in 16nm CMOS
    - 4-7 nm on immediate horizon and should allow cost reduction
  - Within emerging capabilities
  - Start at 100 Gbps instead (1/10 the cost)?

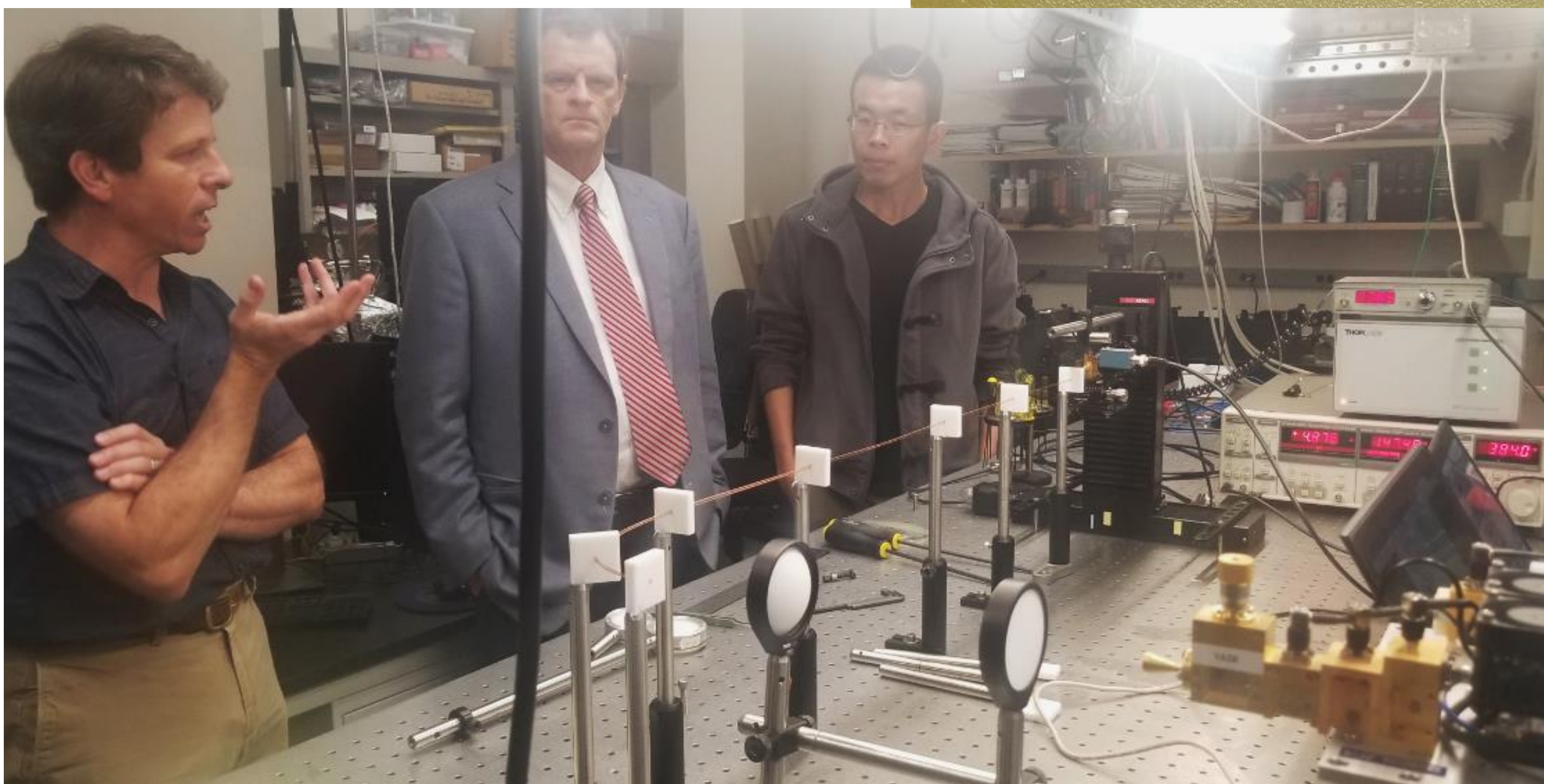
Opportunities – Measurements

- Real <u>cable</u> measurements would help
  - These modes certainly exist, but what exactly is attenuation?
  - Best/reasonable antenna/interface designs?
  - Real-world impairments: bends, splices, taps, etc.
- How good is the log-normal model for waveguide modes' xtalk?
  - Might this xtalk be larger?

- Even 10% of projected data rates >> "G.mgfast"

Brown University – current NSF work

Professor Dan Mittleman



What about yet-higher-order modes?

- They exist!
- Higher bandwidths, but attenuation?
  - Unknown for now
  - Likely need even more antennas/wire (MIMO)
  - 10 meters (instead of 100m) might work
    - Not clear if waves could be focused like surface waves by MIMO processing to "hug the wires" as they separate and go to individual homes
    - Grounded shield would contain them though
  - PDSL? (P=Petabit or 10^{15})

- TDSL will probably be enough for now

Conclusions

- TDSL is technically feasible with 100 pairs and phantoms used for backhaul
  - Also roughly 1 Tbps @100m, 100Gbps at 300m, 10 Gbps at 500m
    - But of course on ALL 100 pairs used together
    - Could be very useful for 5G cell multitude

- Terabit/s DSL per home (or small cell) also appears feasible
  - Using waveguide modes and vectoring – SINGLE pair
  - Measurements of attenuation would help refine rate/range
    - Probably with MIMO-channel characterization used
    - Could be expensive to prototype
      - Because of processing/converter speeds involved

- Is it worth it? (or should we spend $4 Trillion to replace all the copper with fiber instead, say in the next 3-5 years ….. Or century?)
  - Would 5G small cells be accelerated since this would reduce deployment cost?

Acknowledgements and Refs

- Prof. Joe Kahn, Stanford U.
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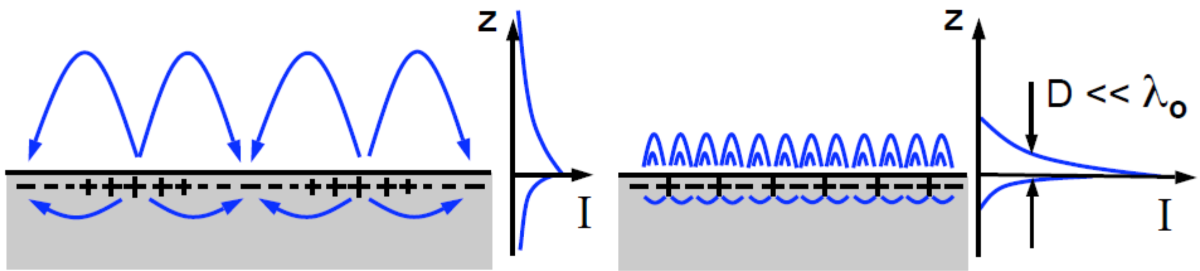
- Dr. S. Galli, Huawei
- Prof. Leonid Kazovsky, Stanford U.

- J.C. Wiltse, “Surface-Wave Propagation on a Single Metal Wire or Rod at Millimeter-Wave and Terahertz Frequencies,” Microwave Symposium Digest, 2006. IEEE MTT-S International, 11-16 June 2006.
- R.E. Collin, “Hertzian Dipole Radiating Over a Lossy Earth or Sea: Some Early and Late 20 th-Century Controversies” IEEE Ant and Prp. Magazine, Vol 46, No. 2, April 2004.
- T.I.Jeon, J. Zhang, and D. Grischkowsky, “THz Sommerfeld wave propagation on a single metal wire,” Appl. Phys. Letters, Vol 86, 2005.

Back UP

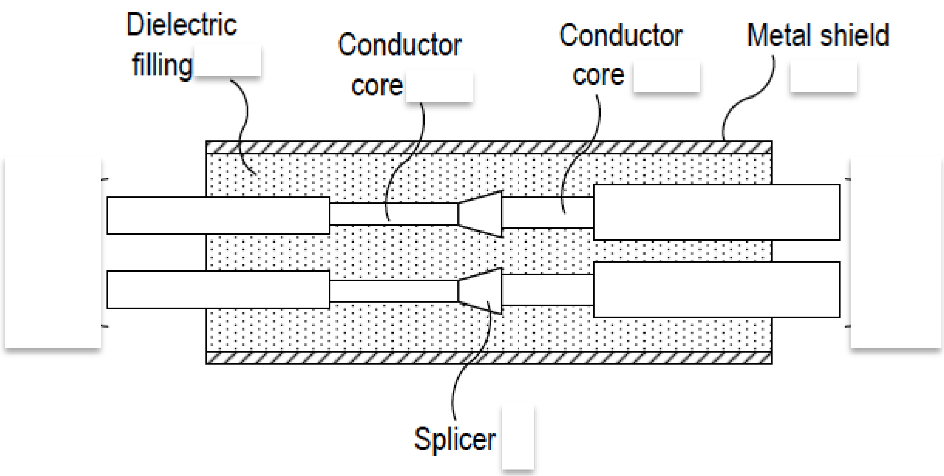
Bare metal wire waveguide

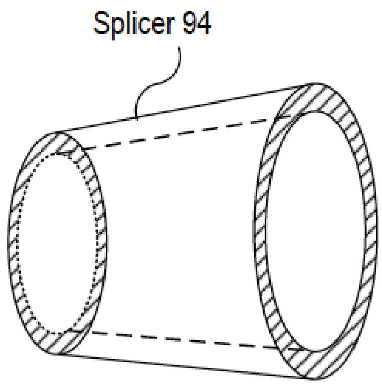


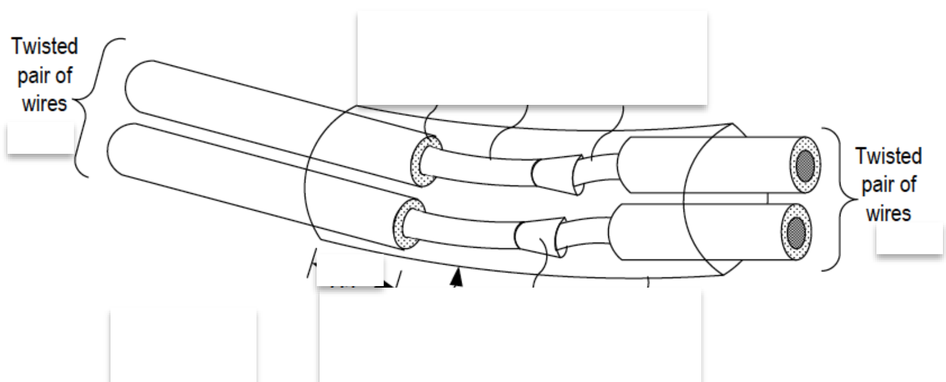
- Surface plasmon polariton
  - EM surface wave that travels along an interface between metal (negative permittivity) and dielectric (positive permittivity) based on surface electron density changes below metal's plasma frequency
    - Phase velocity and group velocity is same (like free space) → no dispersion if frequency is way below plasma frequency
  - E-field decays exponentially vertical to the wire
    - → energy is confied near the conductor so no 1/r type of path loss. Only small ohmic loss due to electron scattering → small in materials with high conductivity and high frequency
    - → Loss about 0.1%~0.25% of field strength in 1cm → 0.86dB/m ~ 2.1dB/m @ 0.25THz
  - Problems
    - TM mode → Hard to generate radially polarized EM wave & low coupling coefficient
    - Need to be straight → lose energy due to bending
    - Connecting two metal wires are not easy

https://nanohub.org/resources/1852/download/2006.10.05-ece695s-l09.pdf

Splicer


Dielectric filling
Conductor core
Conductor core
Metal shield
Splicer


Splicer 94


Twisted pair of wires
Twisted pair of wires