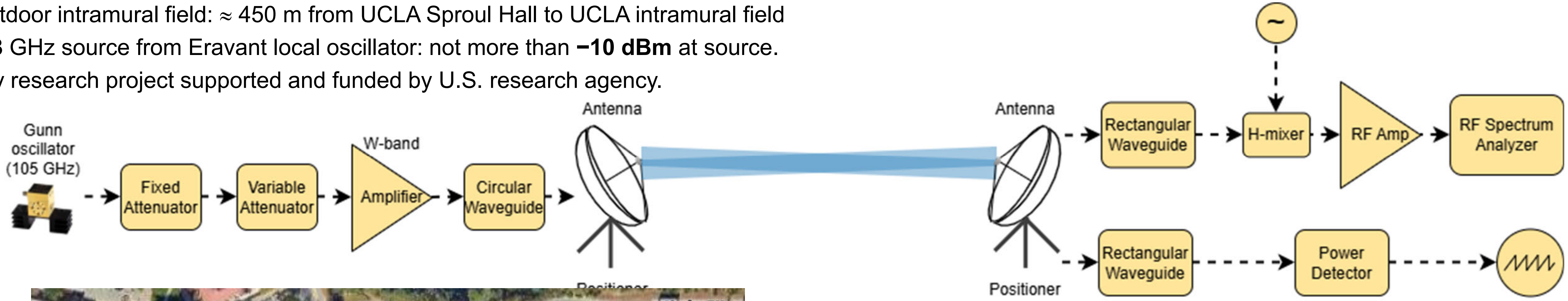
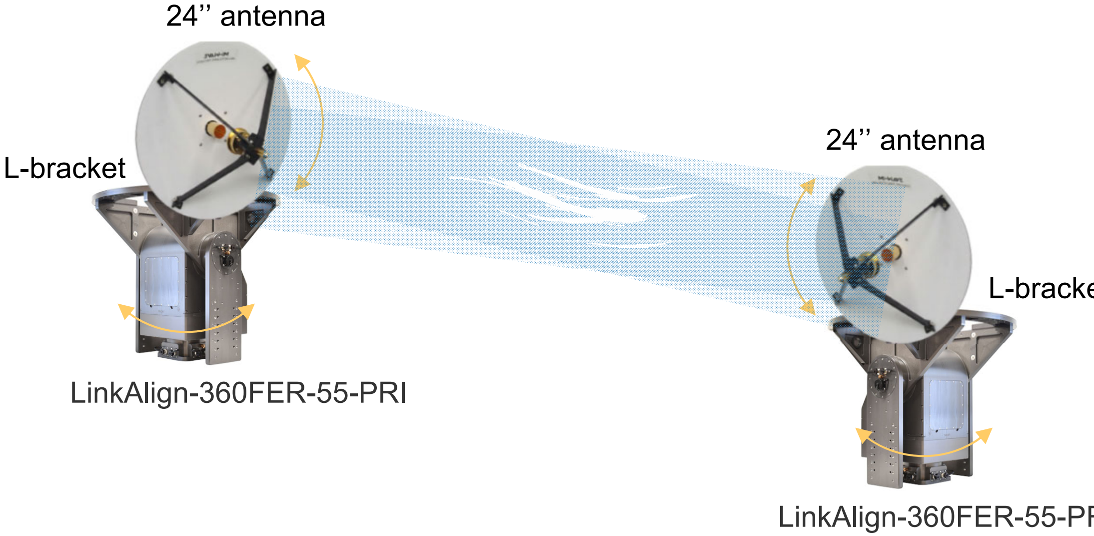
UCLA: 96 to 108 GHz millimeter-wave communications testing, 7/27/2026 – 8/7/2026 (preferred location)

- UCLA outdoor intramural field: ≈ 450 m from UCLA Sproul Hall to UCLA intramural field
- 96 to 108 GHz source from Eravant local oscillator: not more than **−10 dBm** at source.
- university research project supported and funded by U.S. research agency.





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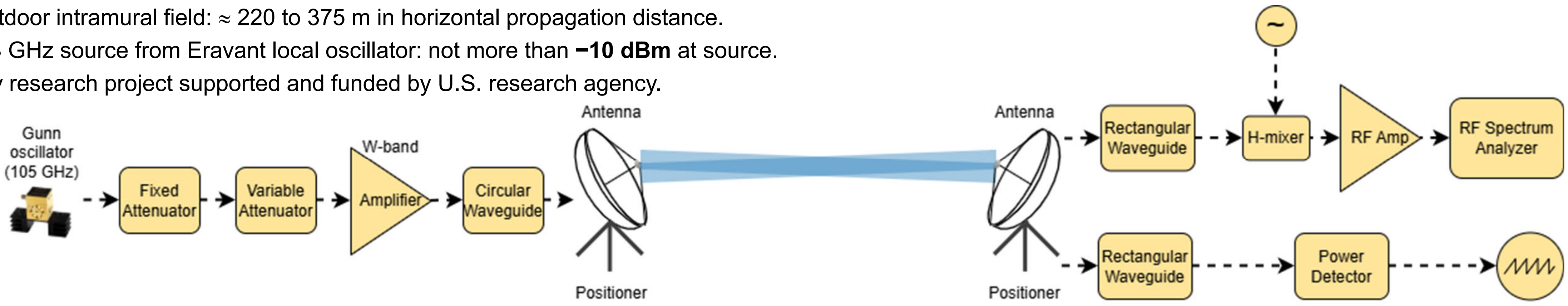
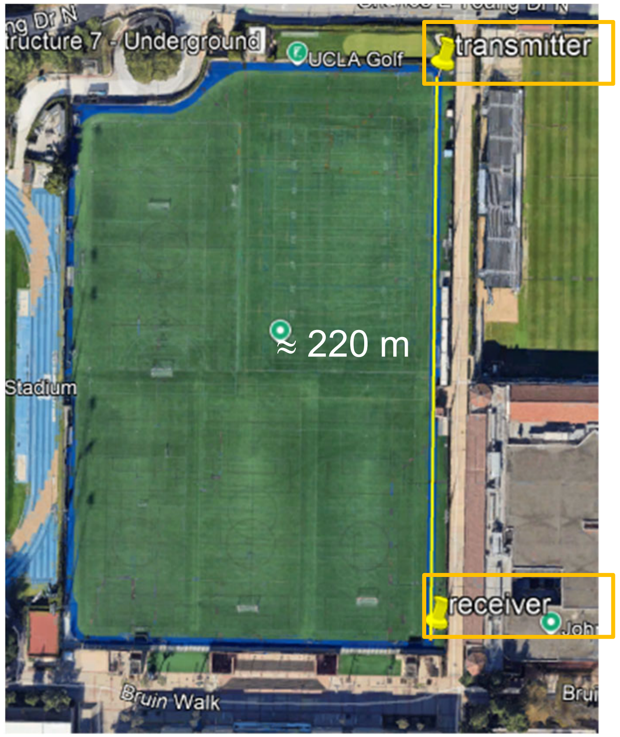
Wong group, Mesoscopic Optics and Quantum Electronics Laboratory, University of California Los Angeles

UCLA: 96 to 108 GHz millimeter-wave communications testing, 7/27/2026 – 8/7/2026 (backup location)

- UCLA outdoor intramural field: ≈ 220 to 375 m in horizontal propagation distance.
- 96 to 108 GHz source from Eravant local oscillator: not more than **−10 dBm** at source.
- university research project supported and funded by U.S. research agency.



UCLA intramural field



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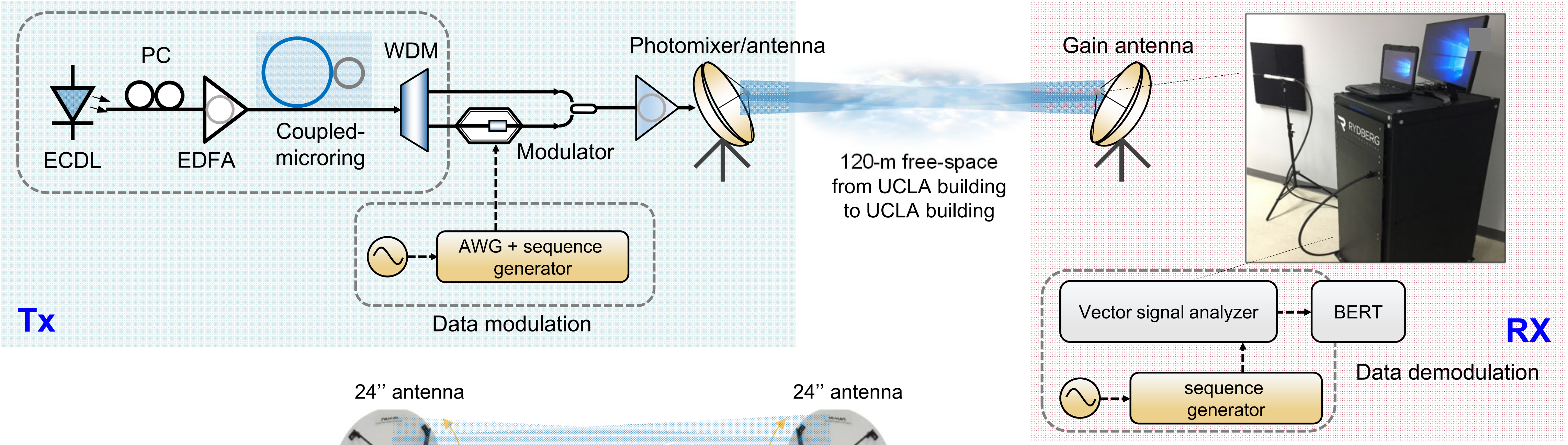
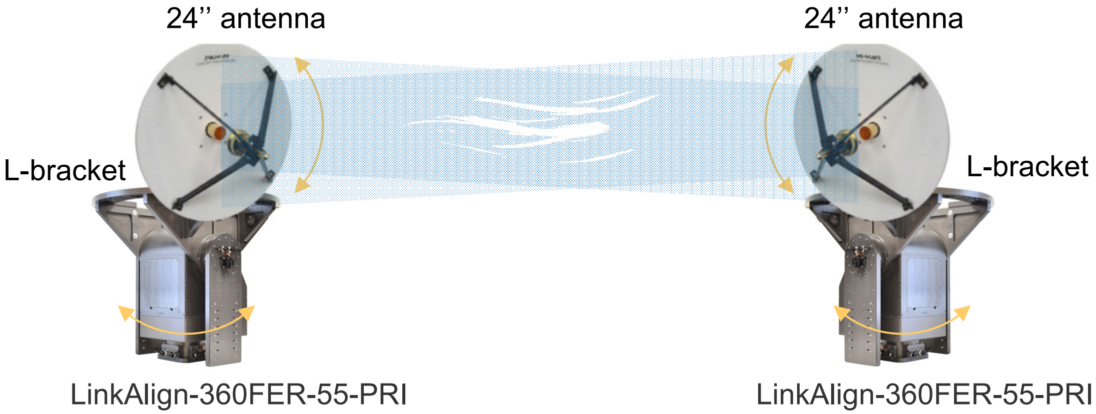
UCLA: 96 to 108 GHz millimeter-wave communications testing, 7/27/2026 – 8/7/2026

- 96 to 108 GHz source from Eravant local oscillator: not more than **−10 dBm** at source.
- low-power transmitter, with good research receiver sensitivity down to ~ 1 to 10 $\mu V/m/Hz^{1/2}$ and spectral densities down to -60 to -80 dBm/Hz.
- test out different software codes for low-error and stable data transmission, such as 5G codes, orthogonal frequency division multiplexing codes, etc.





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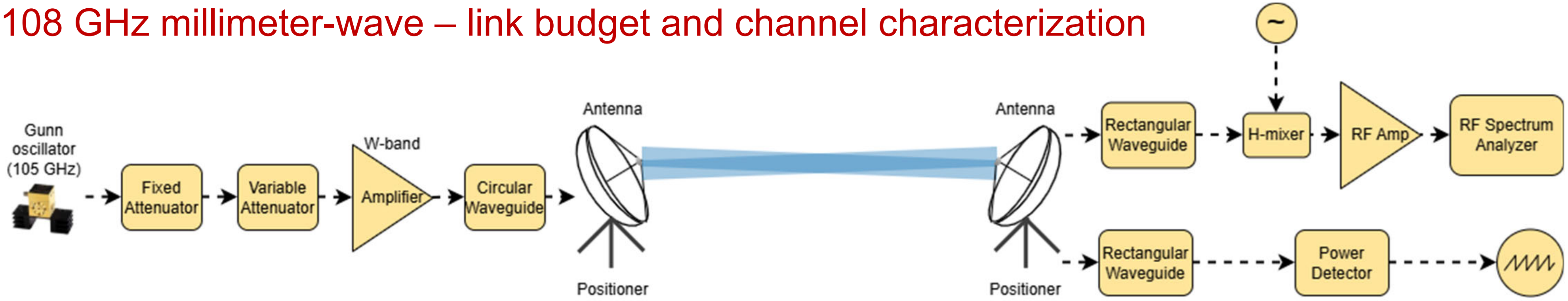
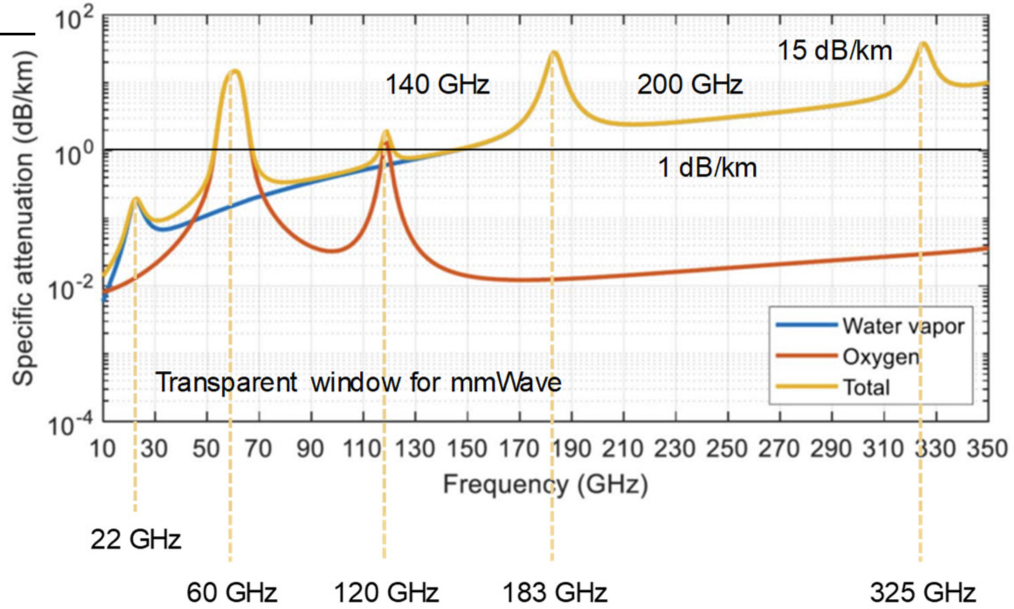
UCLA: 96 to 108 GHz millimeter-wave – link budget and channel characterization



Parameter	Symbol	Value / Assumption
Center frequency	f_0	**96 to 108 GHz**
Signal bandwidth	B	**1 GHz**
Transmit power (at mmWave)	P_T	**−10 dBm**
Antenna gain (Tx/Rx)	G_T/G_R	**51 dBi / 51 dBi** (MI-Wave 24" Cassegrain, 3 dB BW≈0.4°)
Free-space distance	D	**220 to 375 m**
Free-space path loss	$FSPL$	**114.03 dB** (90 GHz, 120 m)
mmWave atmospheric loss	L_{atmo}	**1 (to 10) dB/km**
Estimated received power	P_R	**−22.15 dBm** (-23.23 dBm) $= P_T+G_T+G_R-FSPL-L_A$
Receiver noise figure (assumed)	NF	**7.5 dB**
Equivalent noise temp.	T_{eq}	**≈ 1539 K** $= 290(10^{NF/10}-1)$
Noise power (in 1 GHz)	N	**−76.07 dBm** $= 10\log10(kT_{eq}B)+30$
Estimated SNR after Rx	SNR_{ch}	**≈ 53.92 dB** (52.84 dB) $= P_R-N$
Initial Tx SNR (at 100 GHz)	SNR_{TX}	**≈ 50 dB** [1]
Estimated SNR after Rx	SNR_{total}	**≈ 48.52 dB (48.18 dB)** $=10\log_{10}(10^{-SNRch/10}+10^{-SNRTx/10})$
Link margin		**≈ 38.02 dB (=48.52−10.5) (37.68 dB)**



Attenuation coefficient:

$$\gamma = \gamma_o + \gamma_w = 0.1820 f \left(N''_{Oxygen}(f) + N''_{Water\,Vapour}(f) \right) \qquad \text{(dB/km)}$$

complex refractivities

$$N''_{Oxygen}(f) = \sum_{i\,(Oxygen)} S_i F_i + N''_D(f)$$

$$N''_{Water\,Vapour}(f) = \sum_{i\,(Water\,Vapour)} S_i F_i$$

UCLA: 96 to 108 GHz millimeter-wave – Rayleigh scattering, Mie scattering, and absorption

Standard Atmosphere / **gases only** / sea level:

Optical carrier (visible) – Rayleigh scattering & absorption

- Dominant mechanism: Rayleigh scattering by molecules / gaseous absorption is negligible over km-scale paths
- Rayleigh scattering: $\gamma_R(\lambda) \propto \lambda^{-4}$ → shorter wavelengths attenuate more
- Typical gas-only attenuation for Visible (dB/km) estimated only with Raleigh scattering:

    400 nm: ~0.18 | 450 nm: ~0.11 | 500 nm: ~0.073

    550 nm: ~0.050 | 600 nm: ~0.035

    650 nm: ~0.025 | 700 nm: ~0.019

(V: visibility)

More realistic condition: fog/aerosol exist: (Mie scattering)

- Haze V = 10 km: Optical 0.3–0.5 dB/km vs. mmWave ~0.2–1 dB/km
- Mist V = 5 km: Optical ~0.6–1.0 dB/km vs. mmWave ~0.3–1.5 dB/km
- Light fog V = 1 km: Optical ~3.5–4.3 dB/km vs. mmWave ~1–3 dB/km
- Dense fog V = 0.2 km: Optical ~19.6 dB/km vs. mmWave ~2–6 dB/km
- Very dense V = 0.05 km: Optical ~78 dB/km vs. mmWave ~4–10 dB/km

mmWave – Rayleigh scattering & absorption

- Dominant mechanism: Molecular absorption by O_2 and H_2O
- Spectral structure: Strong absorption lines (O_2 near 60 & 118.75 GHz, H_2O at 22.235 & 183.31 GHz) separated by atmospheric windows (~35, 90, 140, 220 GHz)
- Model shorthand: $\gamma_{gas}(f)=\gamma_{O2}(f)+\gamma_{H2O}(f) = \gamma_{O2}(f)+\gamma_{H2O}(f)$ [dB/km]; values increase with humidity and vary with pressure/altitude
- Typical gas-only attenuation for mmWave (dB/km, sea level, standard humidity):

    100 GHz: ~0.1–0.2 | 120 GHz (O_2 line): ~10–30 (avoid)

    140 GHz (window): ~0.2–0.5 | 160 GHz: ~0.4–0.8

    183 GHz (H_2O line): ~10–50 (avoid)

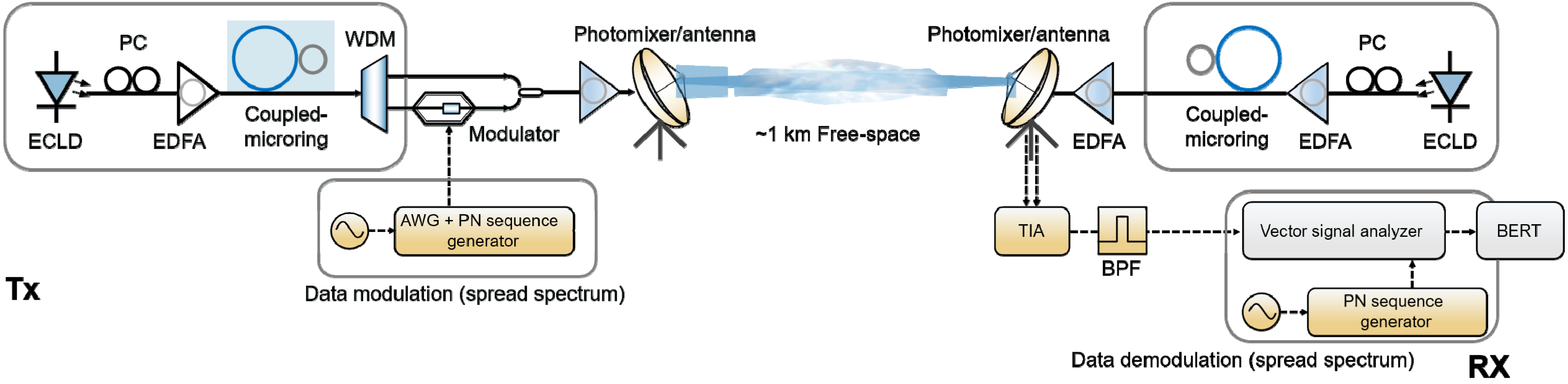
    200 GHz: ~0.8–1.5 | 220 GHz (window): ~0.4–1.0

    240 GHz: ~0.8–1.5 | 275–300 GHz: ~1–3

Kim, McArthur, Korevaar (SPIE 4214, 2001)
Al Naboulsi et al. (Optical Engineering, 2004)
ITU-R P.840-9 (Attenuation due to clouds and fog, 2023)
ITU-R P.676-13 (Attenuation by atmospheric gases, 2022)

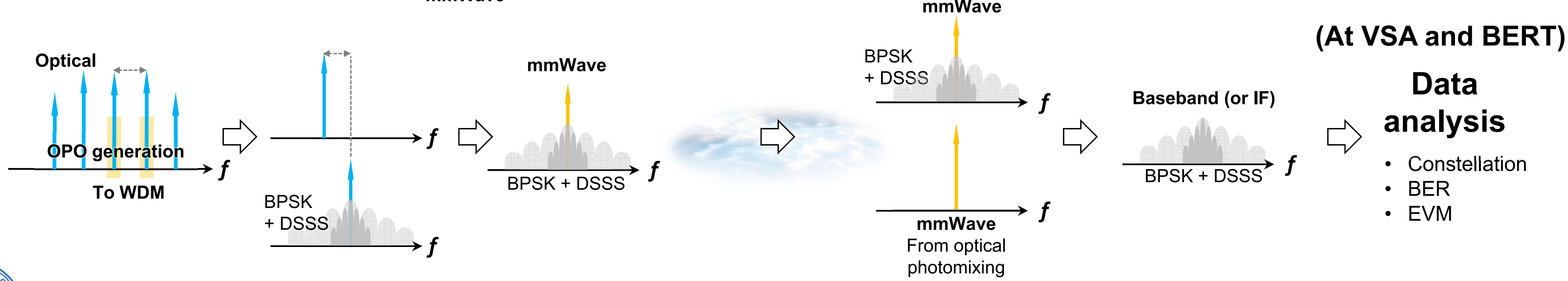
UCLA coherent millimeter-wave – data encoding, decoding and constellation analysis

System configuration:

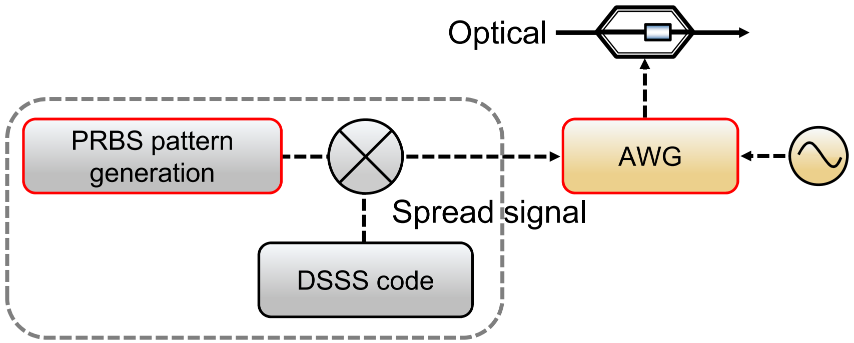


Spectrum conversion flowchart

Optical
mmWave



UCLA millimeter-wave research – components



- We can manually generate PRBS pattern + DSSS spreading and use our possessed AWG to modulate the signal.
- The lists below are the examples that we can use further for the higher modulation.

Components for data communication

- Pattern generator for PRBS data encoding

N4951B Pattern Generator Remote Head

- High-speed PRBS patter generation:

(PRBS7, PRBS15, PRBS23, PRBS31) as the test stimulus

- Sample rate: 32 Gb/s and 17 Gb/s.

- Arbitrary waveform generation

M9384B VXG Microwave Signal Generator

- Frequency range: options: 1 MHz to 14 GHz (F14), to 20 GHz (F20), to 31.8 GHz (F32), and to 44 GHz (F44)
- Frequency resolution: 0.01 Hz
- Channels: Single or Dual-channel. With PCH (phase-coherent) option
- RF modulation bandwidth (internal/external): Up to 2 GHz RF BW (option D20/D21/D2E)
- External analog I/Q input BW vs. RF:

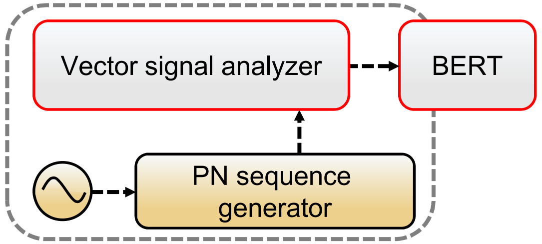
  1.5–3.2 GHz → 1 GHz I/Q BW

  3.2–44 GHz → 2 GHz I/Q BW (full-rate)

M8190A 12 GSa/s Arbitrary Waveform Generator

- 14-bit resolution up to 8 GSa/s
- Variable sample rate from 125 MSa/s to 8 / 12 GSa/s
- Analog bandwidth up to 5 GHz

UCLA millimeter-wave research – components



Components for data communication

- Vector signal analyzer

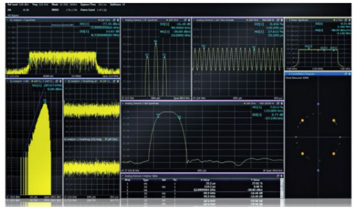
N9042B UXA Signal Analyzer, 2 Hz to 75 GHz (Overspec)

Alternative signal analysis instruments

Rohde and Schwarz RTO2064 - Oscilloscope, 4Ch 6GHz

- **Bandwidth:** 6GHz
- 4 Channels
- 20 Gsample/s sample rate
- 2 Gsample maximum memory depth
- Up to 16-bit vertical resolution

\+ R&S®VSE-K70 Vector Signal Analysis Application



- **Frequency range / BW**
  - same as supported instrument
- Advanced and multi-channel pulse analysis
- Fast measurements with parallel analysis & Supporting floating licenses
- Control multiple instruments from one PC

Infiniium MXR-Series Real-Time Oscilloscopes

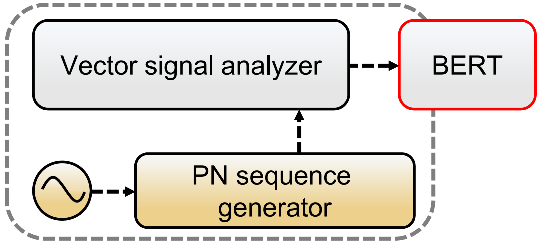
- **Bandwidth:** 0.5 - 6 GHz
- **Analog Channels:** 4 or 8, upgradeable
- **Sampling Rate:** 16 GSa/s
- **Standard Memory:** 200Mpts/ch
- **Waveform Update Rate:** >200,000 wfms/sec

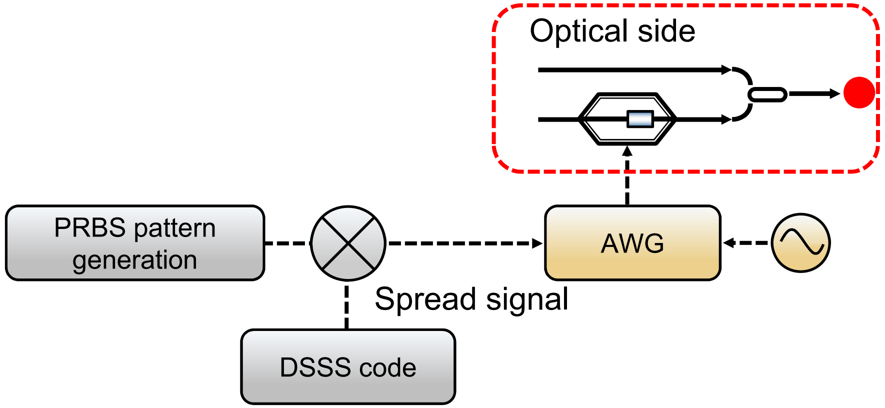
\+ Vector Signal Analysis (89600 VSA Software) - 89601AYAC (Digital Demodulation)

- Provides standard vector signal analysis
- Hardware connectivity
- Center frequency: up to 55 GHz
- IF / BBIQ bandwidth: up to 2.16 GHz

UCLA millimeter-wave research – components

Additional components for data communication



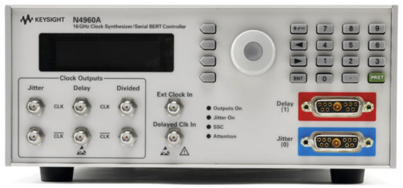


- BERT for the strict BER test

N4952A Error Detector Remote Head 32 and 17 Gb/s

- Available for 4 to 17 Gb/s or 5 to 32 Gb/s configurations
- Full data rate error detection
- PRBS and user-definable pattern, common telecom/datacom test patterns
- Remote head allows placement of signal very close to DUT

N4960A Serial BERT 32 and 17 Gb/s



- Manages synchronization between PG and ED, distributes clock, injects jitter, and supports SSC

- Optical modulation Analyzer

N4392A Optical Modulation Analyzer

- **Symbol rate:** 32 Gbaud
- **Sampling rate:** 63 GSa/s
- **Receiver bandwidth:** 23 GHz
- **Wavelength range:** 1527.6 nm to 1570.01 nm
- **Integrated coherent receiver:** (ICR) test option

- For testing the initial modulated communication data evaluation at transmitter side

UCLA millimeter-wave research – calculation of link signal budget

Two different method for power budget calculation

Friis free-space transmission

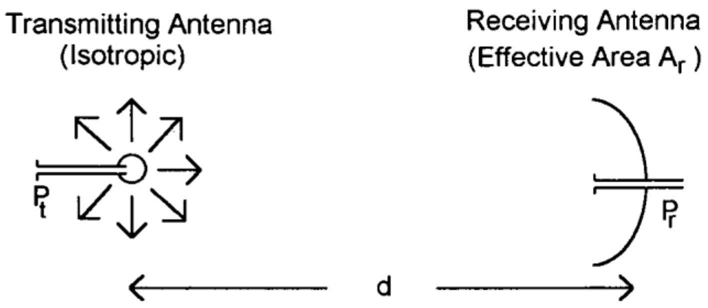


Figure 1. A free-space radio circuit [after Friis].

- Received power efficiency:

$$\frac{P_r}{P_t} = \frac{A_t A_r}{\lambda^2 d^2}$$

Thus, considering these four methods of deriving the Friis transmission formula is not merely a matter of "beating a dead horse," but is an amusing and instructive way of reviewing some basic concepts. This little paper is a follow-up to the "Some Fun with..." article of Jack Nachamkin in the August, 1992 issue of the *Magazine*.

=

Quasi-optical Gaussian-beam derivation

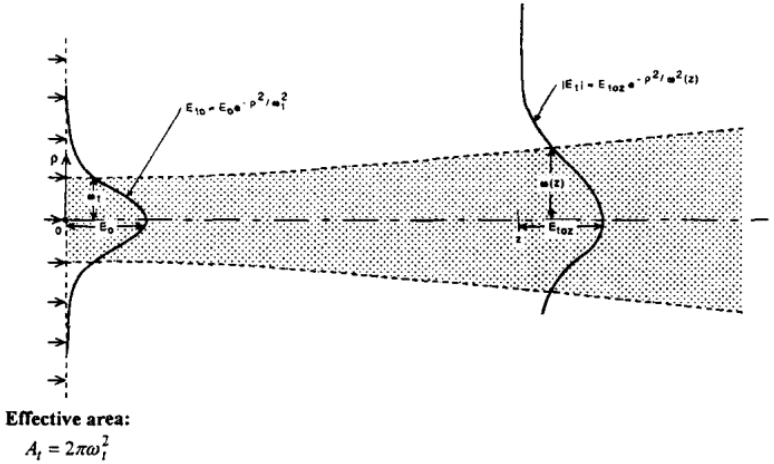


Figure 3. A Gaussian beam (Axially Symmetric). In this figure, the following expressions hold:

- Received power efficiency:

$$\frac{P_r}{P_t} = \frac{A_{te} A_{re}}{\left(\frac{A_{te} + A_{re}}{2} + \lambda^2 d^2\right)}$$

- Rayleigh length of case:

$$z_R = \frac{\pi w_0^2}{\lambda} \approx \mathbf{0.34\ km}$$

- For large value of d (link distance) → reduces to the Friis formula
- Our link 1-km can be considered as *far-field* when f_0 = *100 GHz (λ=3 mm)*

Hogg, David C. IEEE Antennas and Propagation Magazine 35.4 (1993): 33-35
Shaw, Joseph A. American journal of physics 81.1 (2013): 33-37.

Digital signal processing sequence for our coherent link research

1. **For the Transmitter part**

We will shape digital data into a spectrally efficient waveform with our in-house code. And then use AWG to transfer to RF signal applied to modulators.

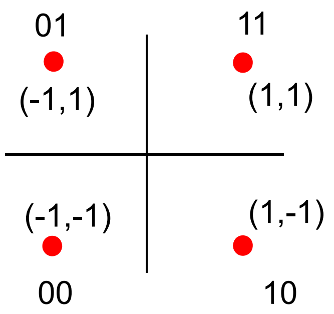
- **PRBS generating**
  - pseudo-random bit sequences with maximal period $2^n - 1$bits, like PRBS7, PRBS9, PRBS15
- **QPSK/QAM16 Mapping**
  - We converts binary data into complex-valued modulation symbols and get the I and Q channel data.
- **Nyquist pulse shaping**
  - For I and Q channel, we shape each datapoint with a Nyquist pulse like a root-raised-cosine (RRC) filter $p\ (t)$ to eliminate ISI at sampling, $x_I(t) = \sum_k s_I[k]p(t - kT)$
- **Pre-emphasis**
  - Pre-compensates frequency-dependent attenuation like RF amplifier roll-off, cables bandwidth limits
  - $X_{TX}(f) = X_{ideal}(f) \cdot H_{pre}(f)$

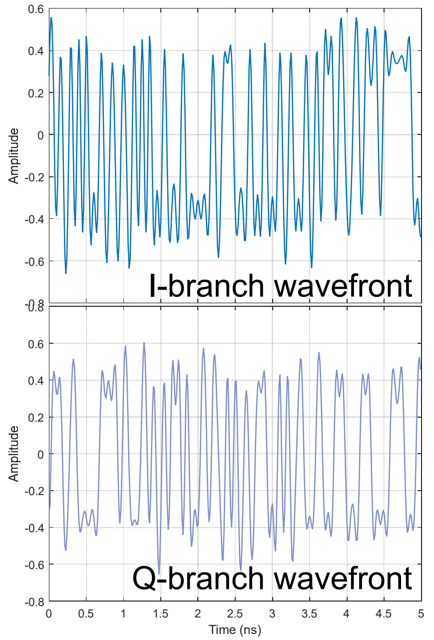
2. **For the Receiver part**

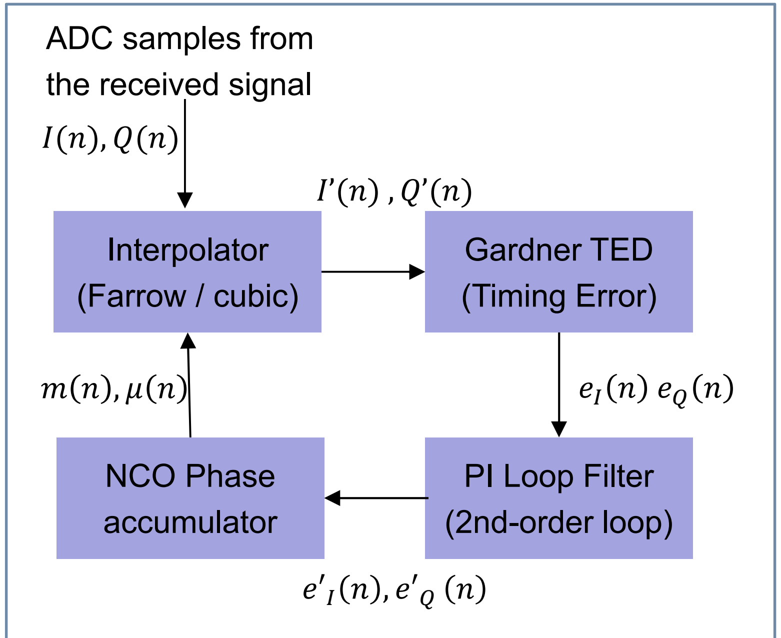
- **Matched Filtering**
  - Matching to the transmitter pulse shaping filter (RRC), $y(t) = x(t) * h_{RRC}(t)$
- **Clock Recovery**
  - Aligning the sampling instants to the optimal symbol decision points.
  - We compensate timing offset and sampling clock mismatch with Gardner timing error detector, using the time error zero mean since the optimal sampling symbol have the perfect symmetry.
  - And we construct a digital timing-locked loop：Interpolator → Gardner TED → Loop Filter→ NCO(numerically controlled oscillator).
- **CMA Equalizer**
  - In our code, we employ an adaptive FIR equalizer to compensate residual group delay and linear channel distortion.
  - The tap coefficients are iteratively updated using the Constant Modulus Algorithm (CMA), which minimizes the deviation of the equalized signal power from a predefined constant modulus corresponding to the QPSK constellation.

PRBS generating

1000010011110…0101110





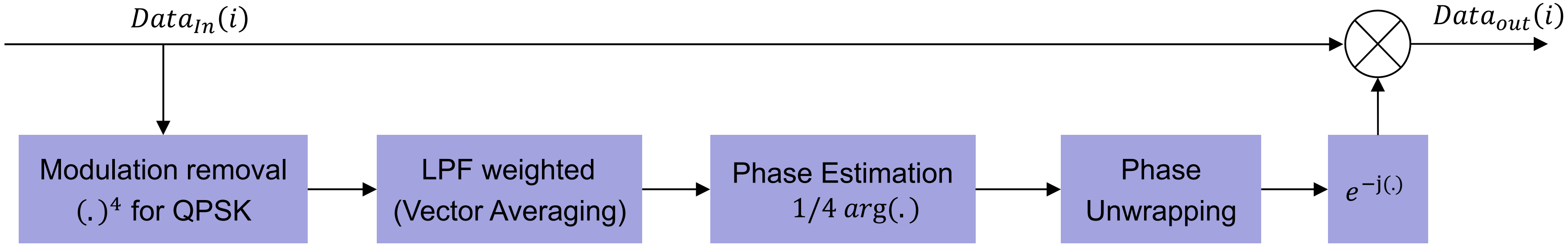


All-digital symbol timing recovery Diagram

Digital signal processing sequence for our coherent link research

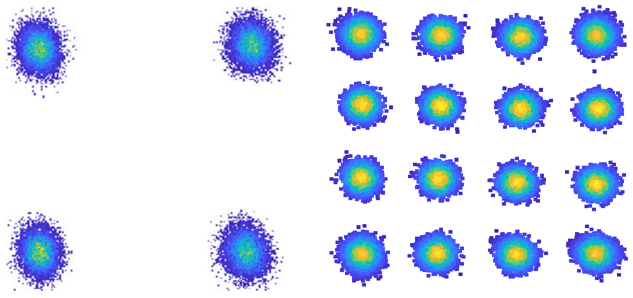
2. **For the Receiver part**

- **Phase Estimation**
  - We compensate laser phase noise and frequency offset between received signal and LO to restore correct constellation orientation before symbol decision.
  - We adopted Viterbi–Viterbi Phase Estimation algorithm with four main steps: 1) modulation removal 2) vector averaging 3) phase estimation 4) phase unwrapping.
  - Specifically, we make an adaptive window alignment for three distinct zones instead of discarding the first and last few bits or zero padding



- **EVM calculating and Constellation map**: Before symbol decision, we will use $Data_{out}(i)$ to calculate EVM and construct constellation map
- **Symbol Decision**
  - We map the $Data_{out}(i)$ to nearest constellation point with hard slicing.
  - For QPSK, we decide I/Q by sign threshold at 0, $I[k] = sign(R\{Data_{out}(i)\ \}), Q\hat{}[k] = sign(I\{Data_{out}(i)\})$
- **De-mapping**
  - Do Inverse operation of the transmitter mapping, and then converts detected symbols back into bit streams
- **BER Counting**
  - We count and compare transmitted and received bit sequences to determines link quality and FEC requirements
  - HD-FEC (hard-decision FEC): typical pre-FEC BER threshold $\approx 3.8\times10^{-3}$ ($\approx$7% overhead)
  - SD-FEC (soft-decision FEC): typical pre-FEC BER threshold $\approx 2\times10^{-2}$ ($\approx$20% overhead)

Constellation Maps by our off-line DSP code



QPSK
EVM =10.8%

QAM16
EVM =6.7%

20Gbaud Symbol rate