Security Level:

The Case for Hybrid Electro-Optical BTS

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Multidisciplinary Team

- Phase Sensitive Innovation (PSI) – Experts in RF photonics and phased arrays.
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- Futurewei, NJ Labs – Cross-disciplinary team in wireless, RF, and optics.
  - S. Galli, M. Kermalli, X.F. Qi
- Work published in:
  - "Multiuser-MIMO transmitter based on optical polar-vector modulators," IEEE Photon. Technol. Lett., vol. 30, no. 21, pp. 1834–1837, Nov. 2018.
  - "A Novel Opto-Electronic Architecture for Large Multi-Band and Multi-Beam Phased Arrays," *IEEE Wireless Communications and Networking* (WCNC), Marrakesh, Morocco, April 15-18, 2019.

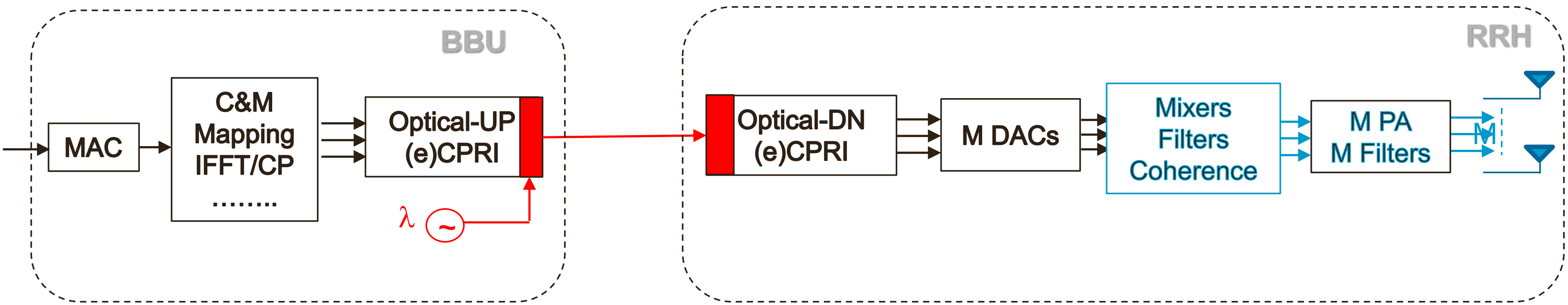
Basic Approach

- **Exploit advances in RF photonics to generate/process RF signals in optical domain/**
  - Wideband processing and multi-band support become easier
- **At the TX:**
  - Upconvert baseband signals to phase locked optical carriers in BBU, transport via single-mode fiber to RRU (no CPRI), and convert to RF via photodetection at RRU.
- **At the RX:**
  - Upconvert RF signals to optical carrier at RRU, transport via single mode fiber to BBU (no CPRI) and perform detection via photodiodes.
- **Lens at TX/RX can be used to perform Hybrid BF in the optical domain to support *beamspace MIMO* with analog spatial FFT/IFFT in the optical domain.**
  - It also facilitates sensing!

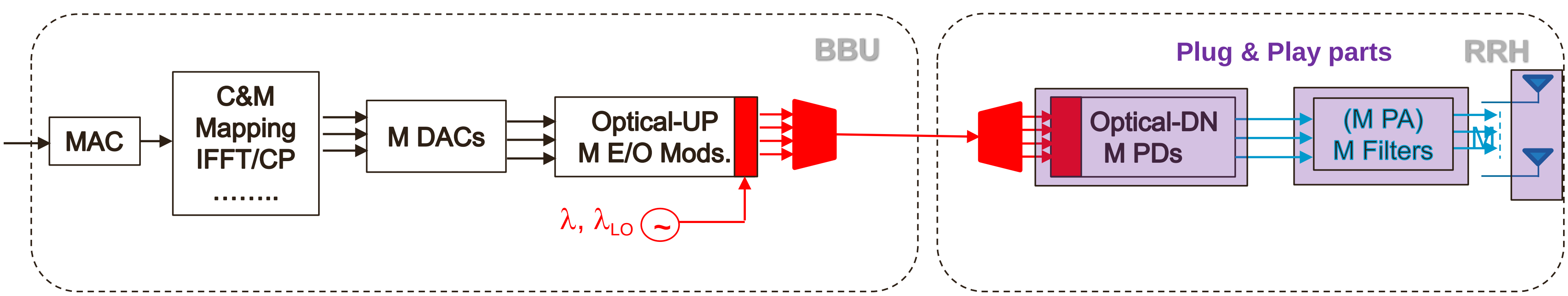
Transmitter (Digital Beamforming)

Digital/BB
Optical
IF/RF
Free Space

Conventional Architecture



Hybrid E/O Architecture (many variants)



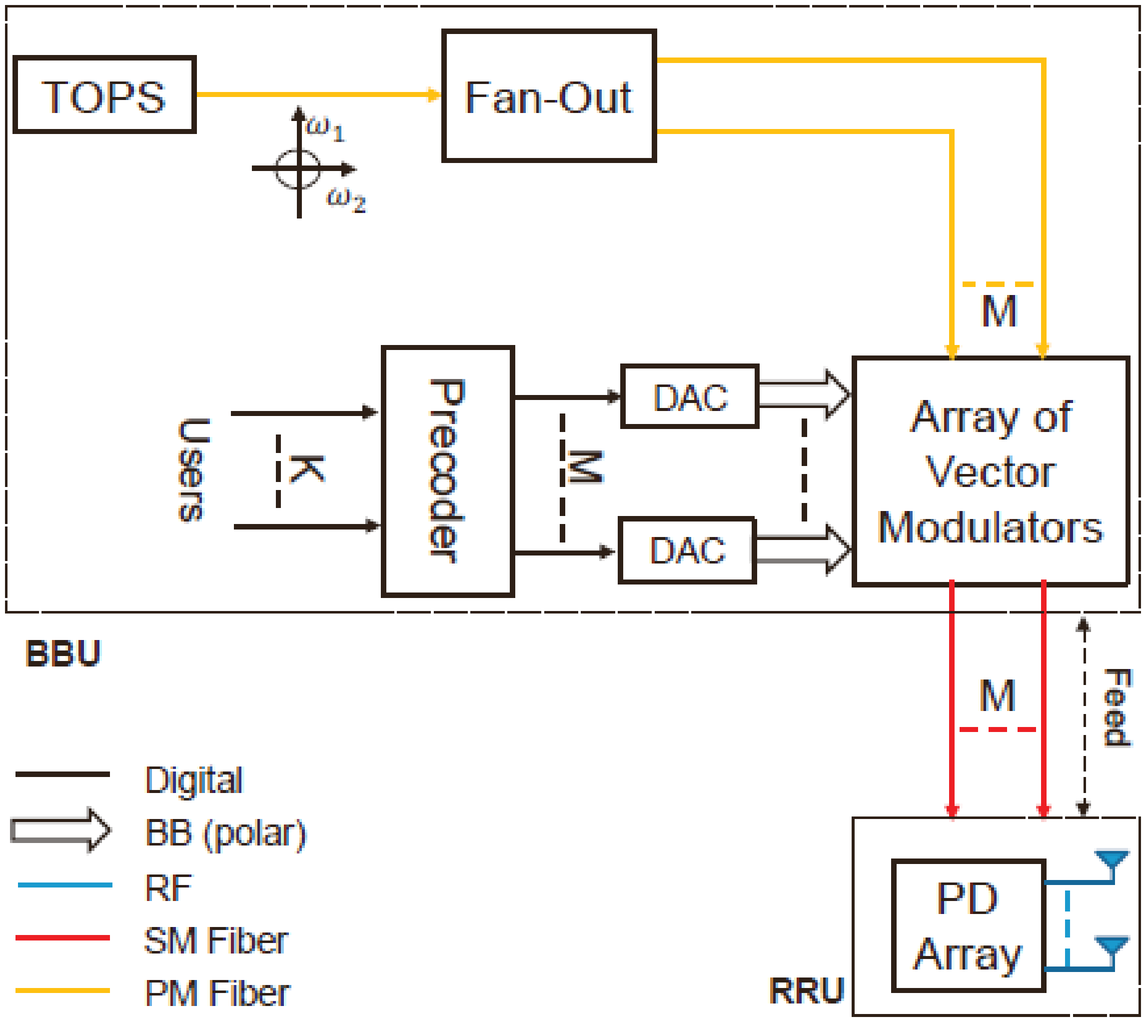
Why Optical conversion?

- Many frequency-dependent (band-specific) devices in an all-RF implementations (filters, mixers, power dividers, hybrid couplers, power amplifiers, etc.).
- I/Q up-converters are characterized by limited operating bandwidth and power & phase imbalance.
- Maintaning coherence between antenna feeds is problematic for >100 antennas due to distribution of LO signal:
  - Physical layout issues related to routing traces to many feeds.
  - Sensitivity of the trace lengths to higher frequencies (very high loss of metallic traces at tens/hundreds of GHz).
- In current (e)CPRI dependent architectures, the RRU cost can become very high as well as its power consumption since RRU supports optical down-conversion and baseband & RF processing.
- All-RF implementations do not scale well antennas and bands.

Hybrid E/O BTS Advantages

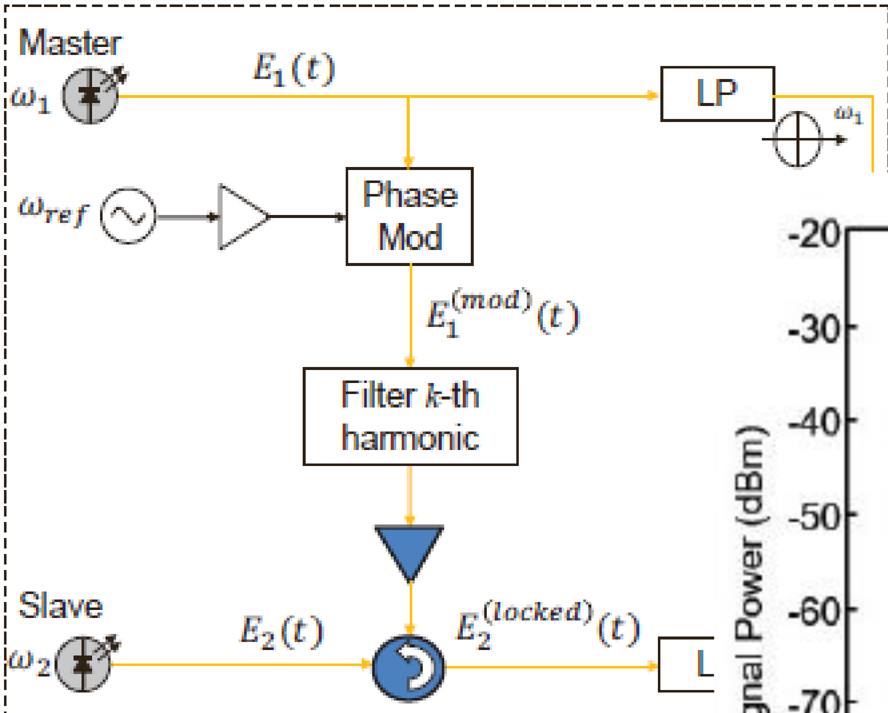
- Common optical part that can support multiple simultaneous bands via tunable laser (e.g., 0.6-70 GHz) and few “plug & play” band-specific ➔ BTS constructions more modular with BOM reduction!
  - BBU and most of RRH are frequency independent.
  - Lighter RRH: much fewer band-specific components which are “plug & play” can be easily swapped in/out and (no mixers, fewer filters, no LO routing network, while ADCs/DACs are only in BBU).
- Naturally supports multi-band operations given the wide bandwidth available at optical frequencies.
- Leverages integration of E/O modulators and photo-detectors.
  - Tremendous advances in microwave photonics, photonic integration, and high-power and highly linear photodiodes.
  - Ultra-small and high-bandwidth electro-optic modulators, complete integration of light sources, modulators, and detectors in a single microwave photonic processor chip with multi-functionality and re-configurability similar to their electronic counterparts.

The Transmitter

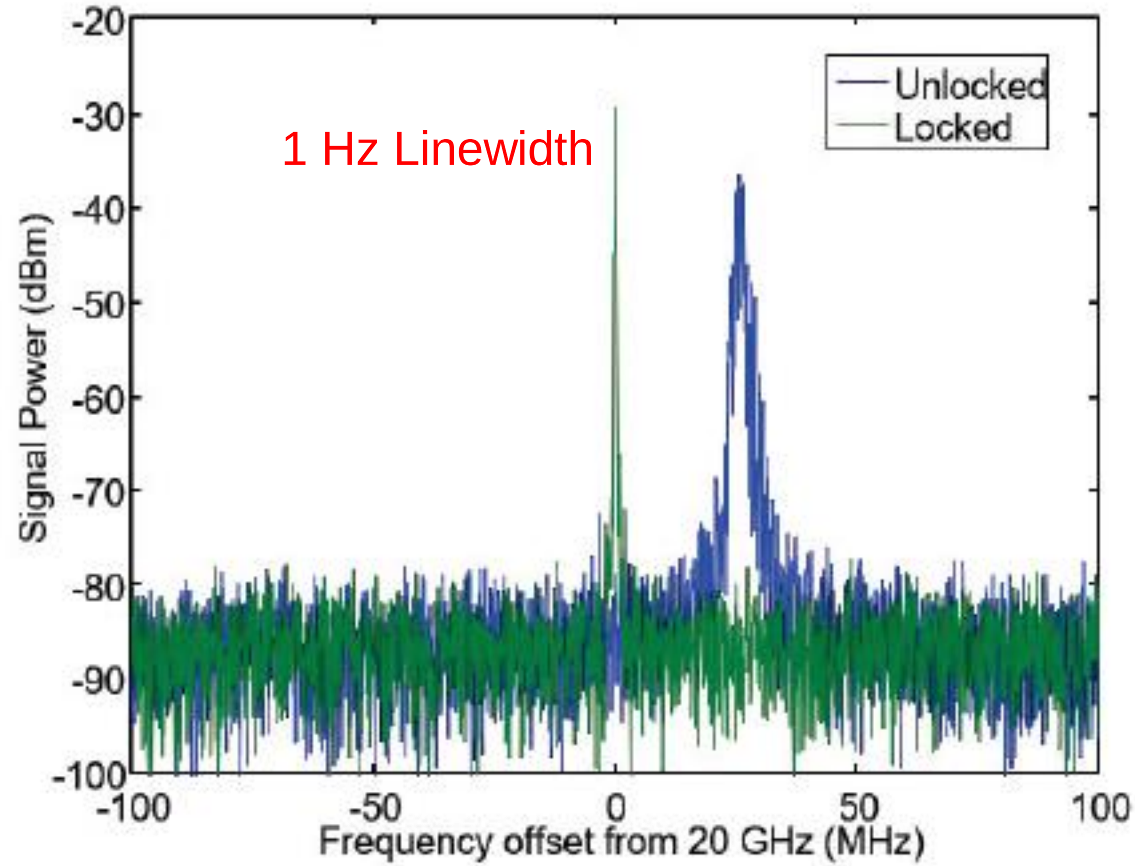


The Tunable Optical Paired Source

$$E^{(\mathrm{TOPS})}(t) = \hat{x}\sqrt{I_1}e^{j[\omega_1 t+\phi_1(t)+\psi_1(t)]} + \hat{y}\sqrt{I_2}e^{j[(\omega_1+\omega_{RF})t+\phi_1(t)+\psi_2(t)]}$$



$\omega_2 - \omega_1 = k\,\omega_{ref} = \omega_{RF}$

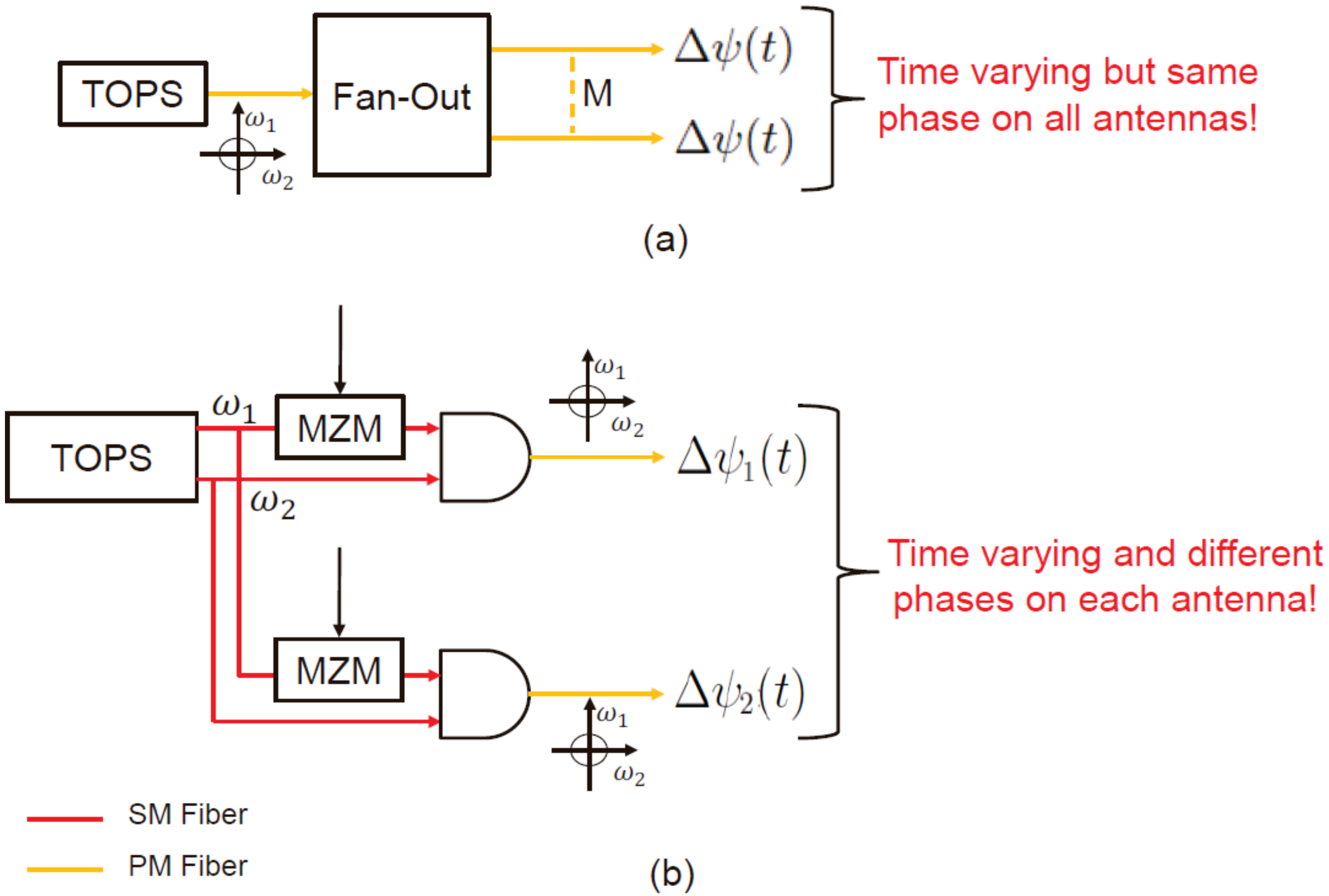


Can be integrated and tuned between 0.6-60 GHz!!

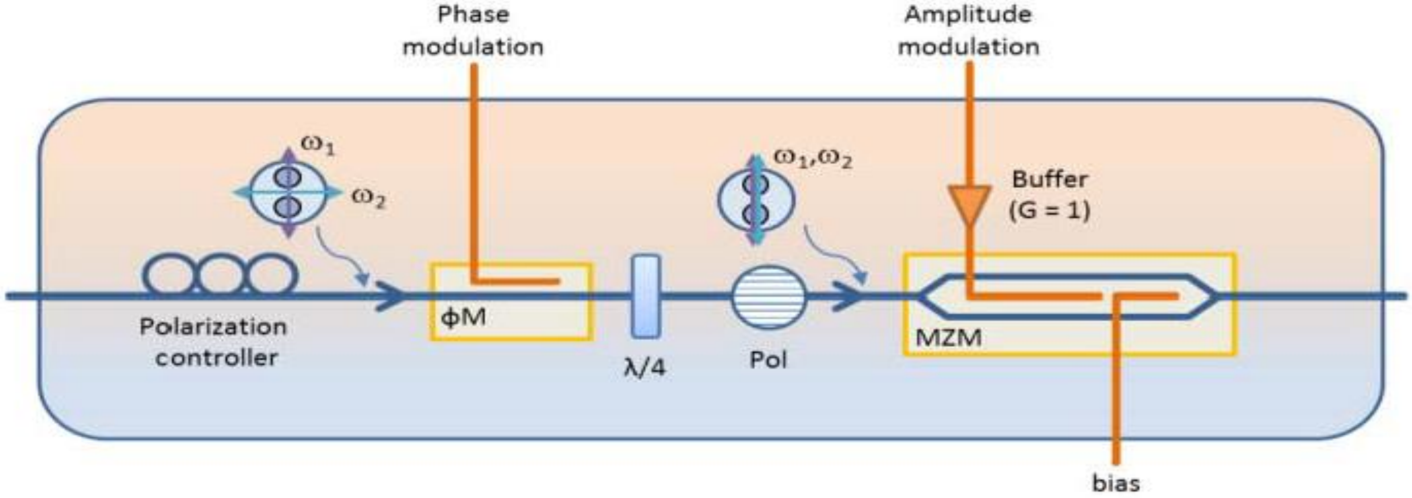
E/O Modulation

- We impose the co-propagation along the same fiber of the modulated carrier and the local oscillator so that random phase variations induced by acoustic, mechanical, and thermal perturbations along the fiber are easily cancelled out at photomixing.
  - This allows a highly coherent system regardless of number of antennas.
- Problem: E/O modulators are polarization-dependent ➔ conventional I/Q modulators cannot be used.
- Solution: new device (Vector Modulator) operating in polar coordinates, implemented with COTS devices.

Fan Out Options



Vector Modulator



$$E_m^{(PC)}(t) = \frac{\sqrt{2}}{2}\left\{\sqrt{I_1}e^{j[\omega_1 t+\phi_1(t)+\psi_1(t)+\frac{\pi V_m^{(pha)}(t)}{3V_\pi}]} + \right.$$

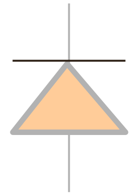
$$\left. + \sqrt{I_2}e^{j[(\omega_1+\omega_{RF})t+\phi_1(t)+\psi_2(t)+\frac{\pi V_m^{(pha)}(t)}{V_\pi}]}\right\}$$

$$E_m^{(VM)}(t) = \left[e^{j\left(\phi_{01}-\frac{\pi V_m^{(amp)}(t)}{2V_\pi}\right)} + e^{j\left(\phi_{02}+\frac{\pi V_m^{(amp)}(t)}{2V_\pi}\right)}\right]\times$$

$$\times\frac{\sqrt{2}}{2}E_m^{(PC)}(t)$$

Photomixing at the RRU

$$
\begin{aligned}
U_1(\mathbf{r},t) &= \sqrt{I_1(\mathbf{r})}e^{j\phi_1(\mathbf{r})}e^{j\omega_1 t} \\
U_2(\mathbf{r},t) &= \sqrt{I_2(\mathbf{r})}e^{j\phi_2(\mathbf{r})}e^{j\omega_2 t}
\end{aligned}
$$

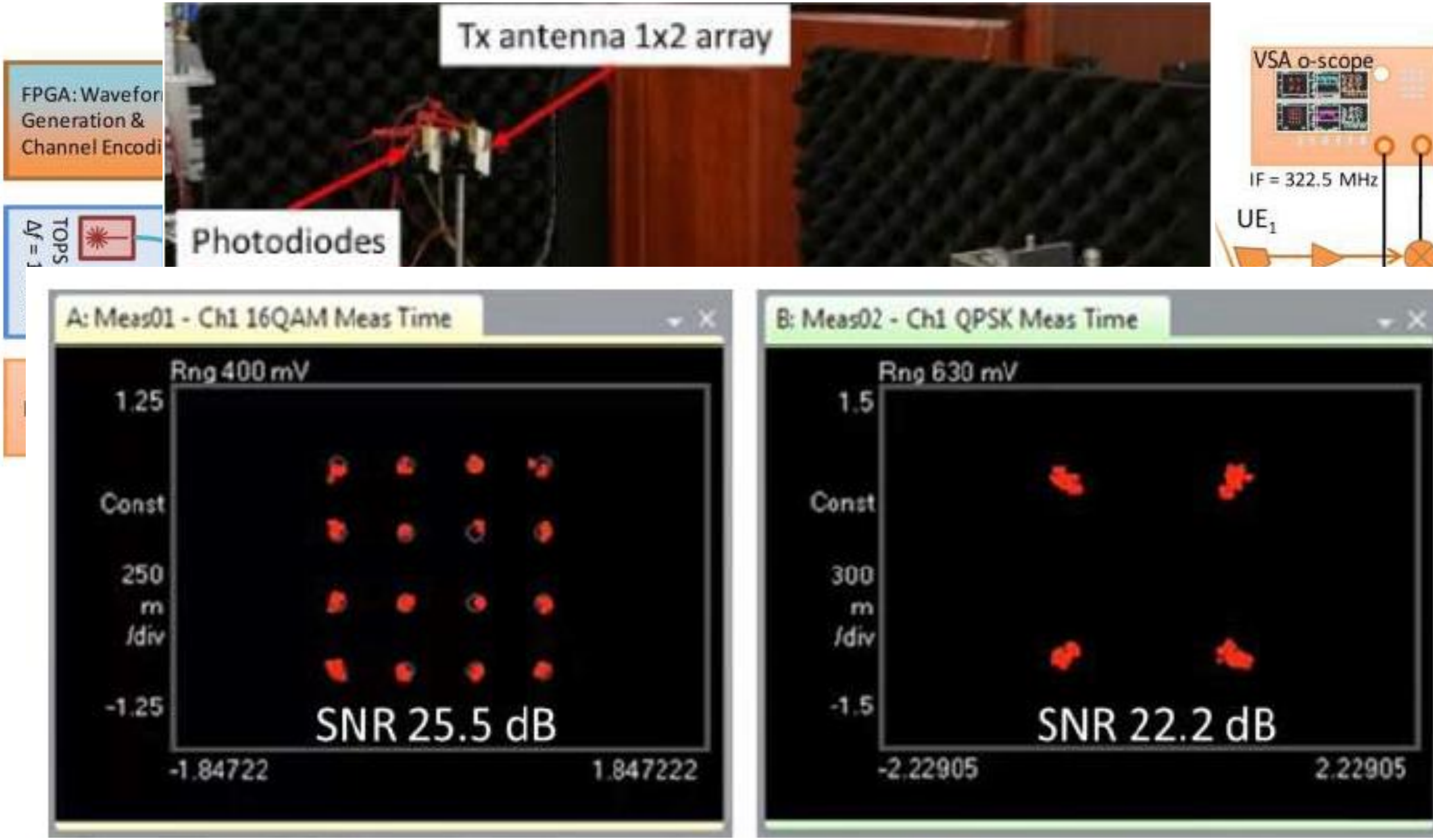


$$
I(\mathbf{r}) = 2I_0(\mathbf{r})\left[1+\cos\left(\omega_{RF}t+\phi_2-\phi_1\right)\right]
$$

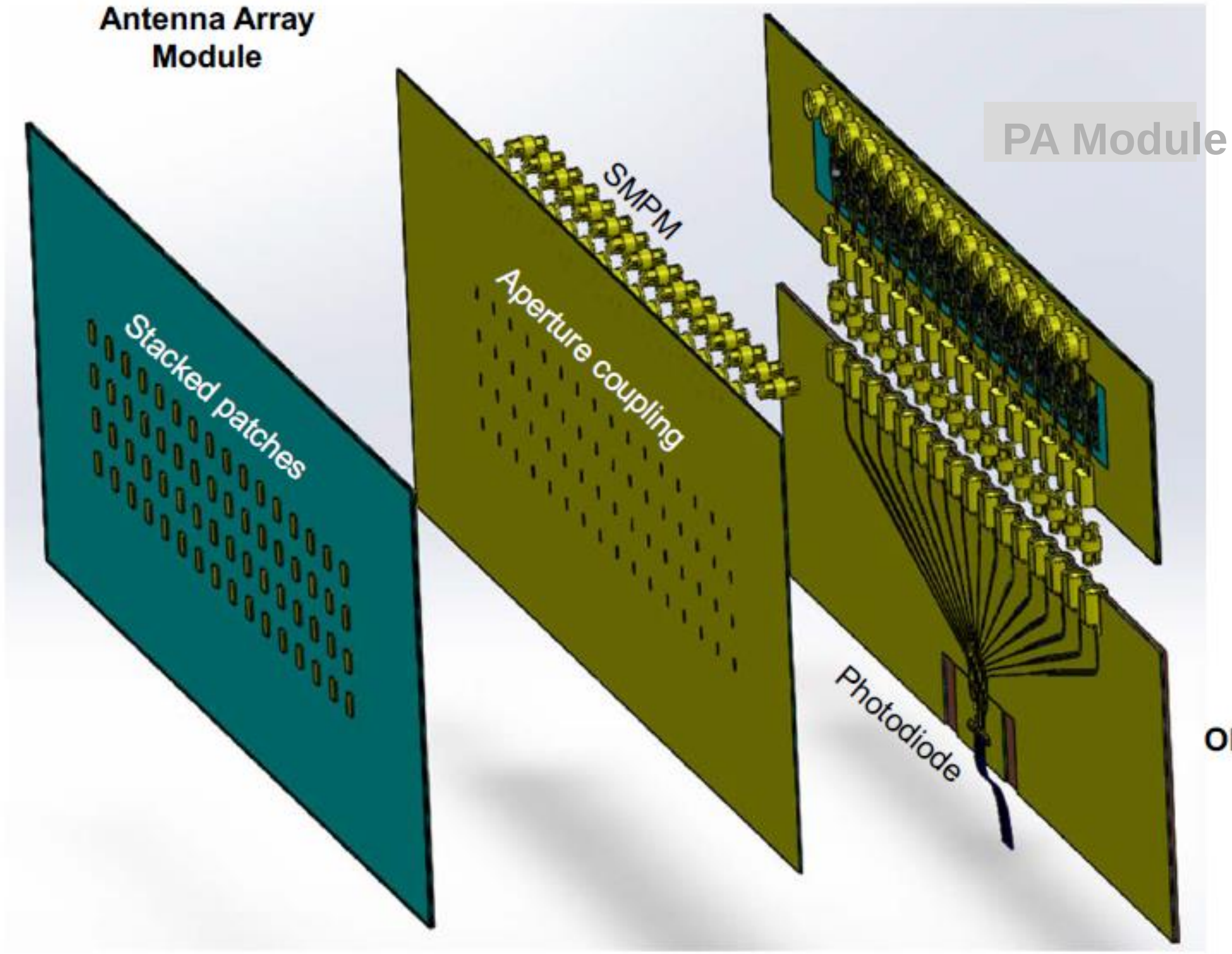
$$
\begin{aligned}
v_m^{(\mathrm{rf})}(t) \approx\ & \frac{\sqrt{I_1 I_2}}{2}\left(1+\frac{\pi}{V_\pi}V_m^{(\mathrm{amp})}(t)\right)\times \\
& \cos\left(\omega_{RF}t+\Delta\psi(t)+\frac{2\pi}{3V_\pi}V_m^{(\mathrm{pha})}(t)\right).
\end{aligned}
$$

$$
i_m^{(\mathrm{rf})}(t) \propto \mathcal{R}v_m^{(\mathrm{rf})}(t) + noise
$$

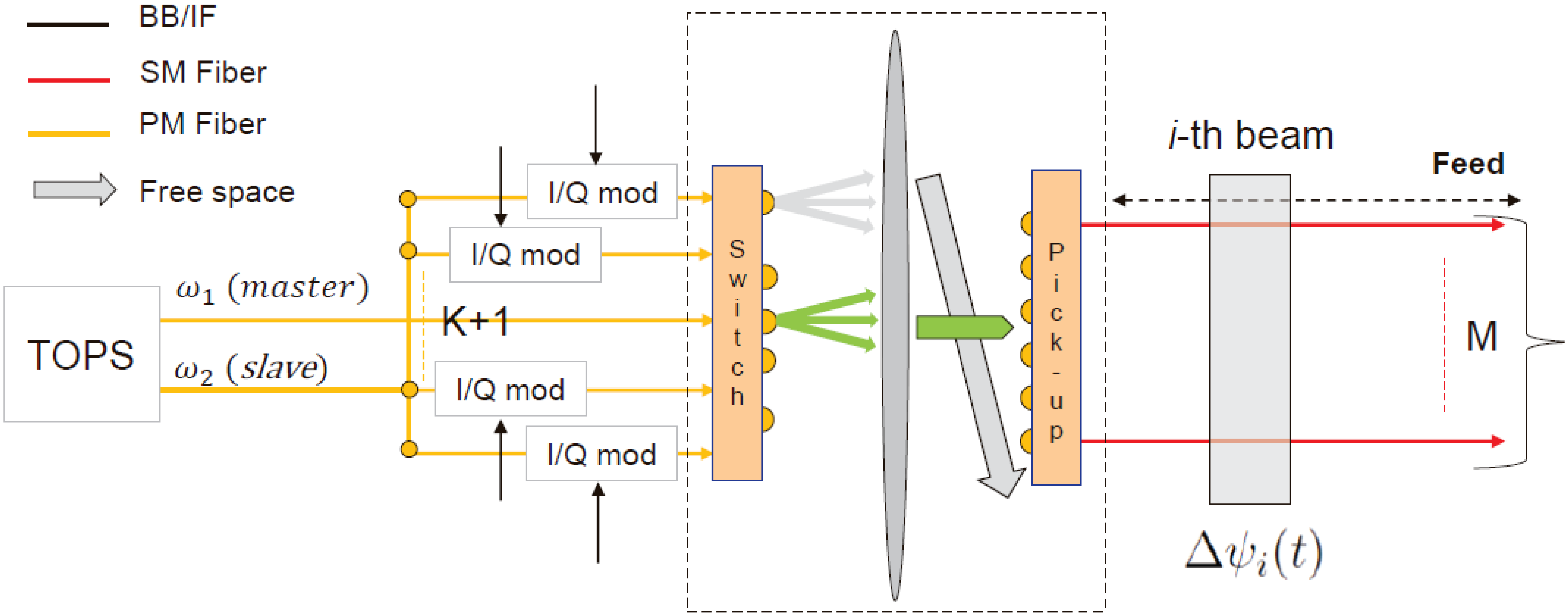
Experimental Verification (PTL Nov 18)



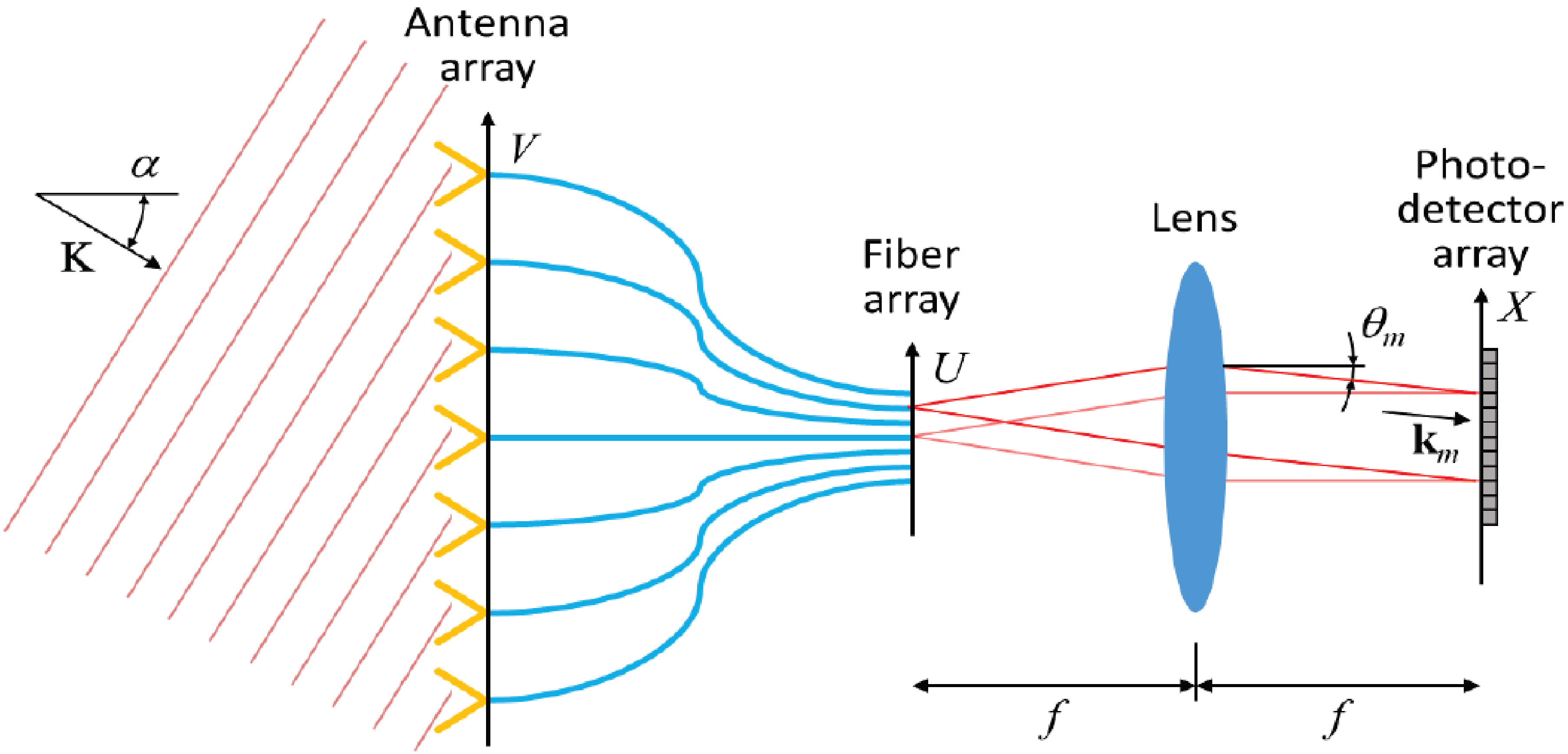
Plug & Play: TX Array (the <u>whole</u> RRH)



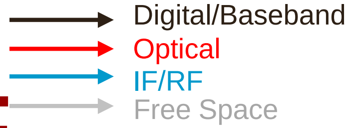
Lens at the TX



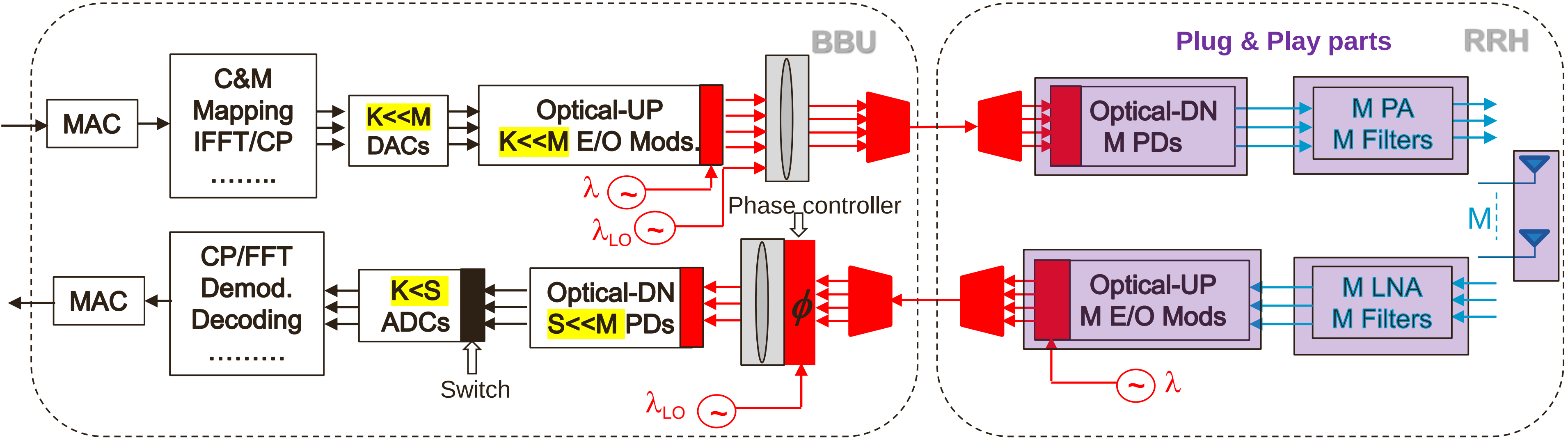
Lens at the RX



Lens: Hybrid Fully Connected BF



- Use of optical lenses greatly reduces issues related to hybrid TX and RX beamforming that all RF solutions have.
  - Use of TX lens allows drastic reduction of DACs and E/O Modulators
  - Use of RX lens for fast fully connected beamforming in optical domain, allowing drastic reduction in number of ADCs and photodetectors as well as the parallel processing of multiple simultaneous wideband beams
  - Very low latency processing, spatial FFT/IFFT at the speed of light!!
- No beam-bandwidth bottleneck!!



Summary

- Presented a BTS architecture with tunable lasers, multi-band and multi-beam support, and characterized by a simple RRU.
- High phase coherence between antenna feeds ensured regardless of the number of antennas by:
  - Generating a pair of phase-locked carriers (1 Hz linewidth).
  - Requiring co-propagation of modulated optical carrier and its reference signal over same fiber.
- Shown by analysis that this could not have been achieved using conventional I/Q optical modulators and developed a new type of modulator operating in polar coordinates.
- Experimental validation (PTL'18) and theory (WCNC'19) reported.
- Microwave photonics and photonic integration will soon enter BTS architecture to support mmW and sub-mmW communications:
  - Allow true promise of software defined radio.
  - Break the beam-bandwidth product bottleneck.

Thank You!

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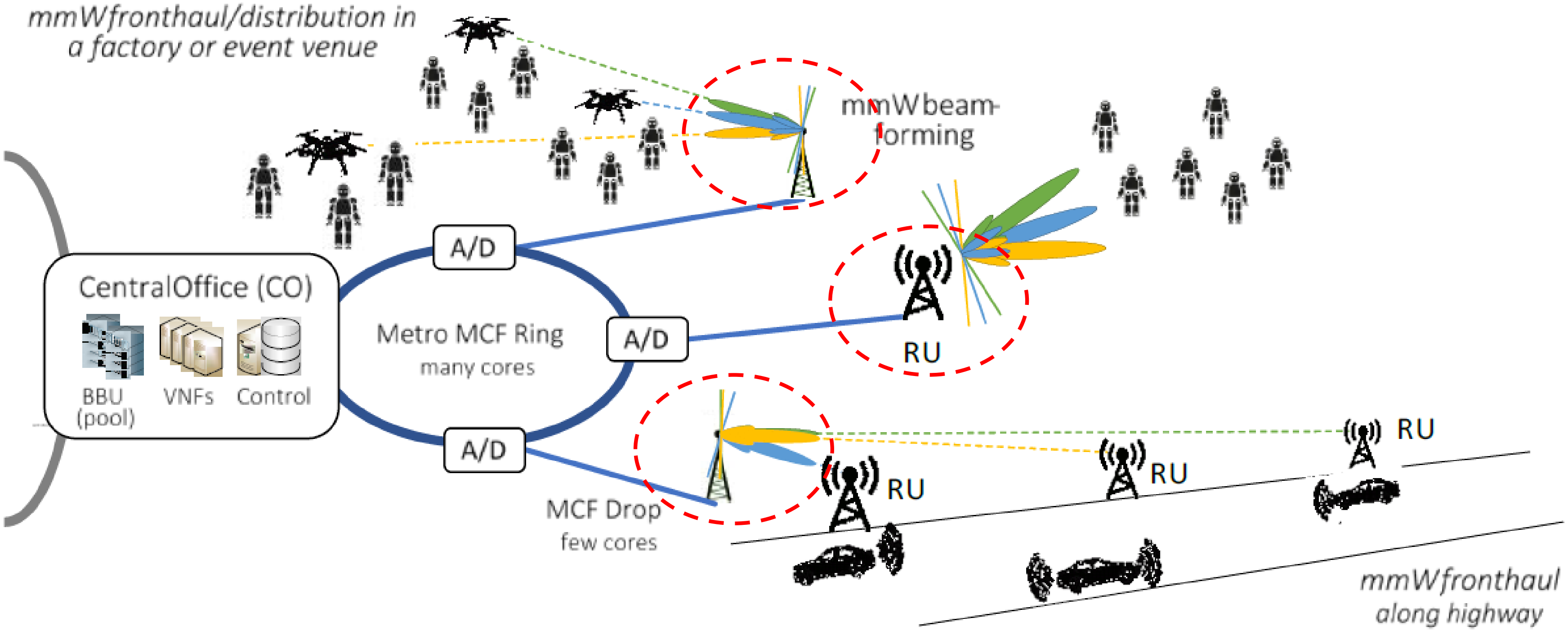
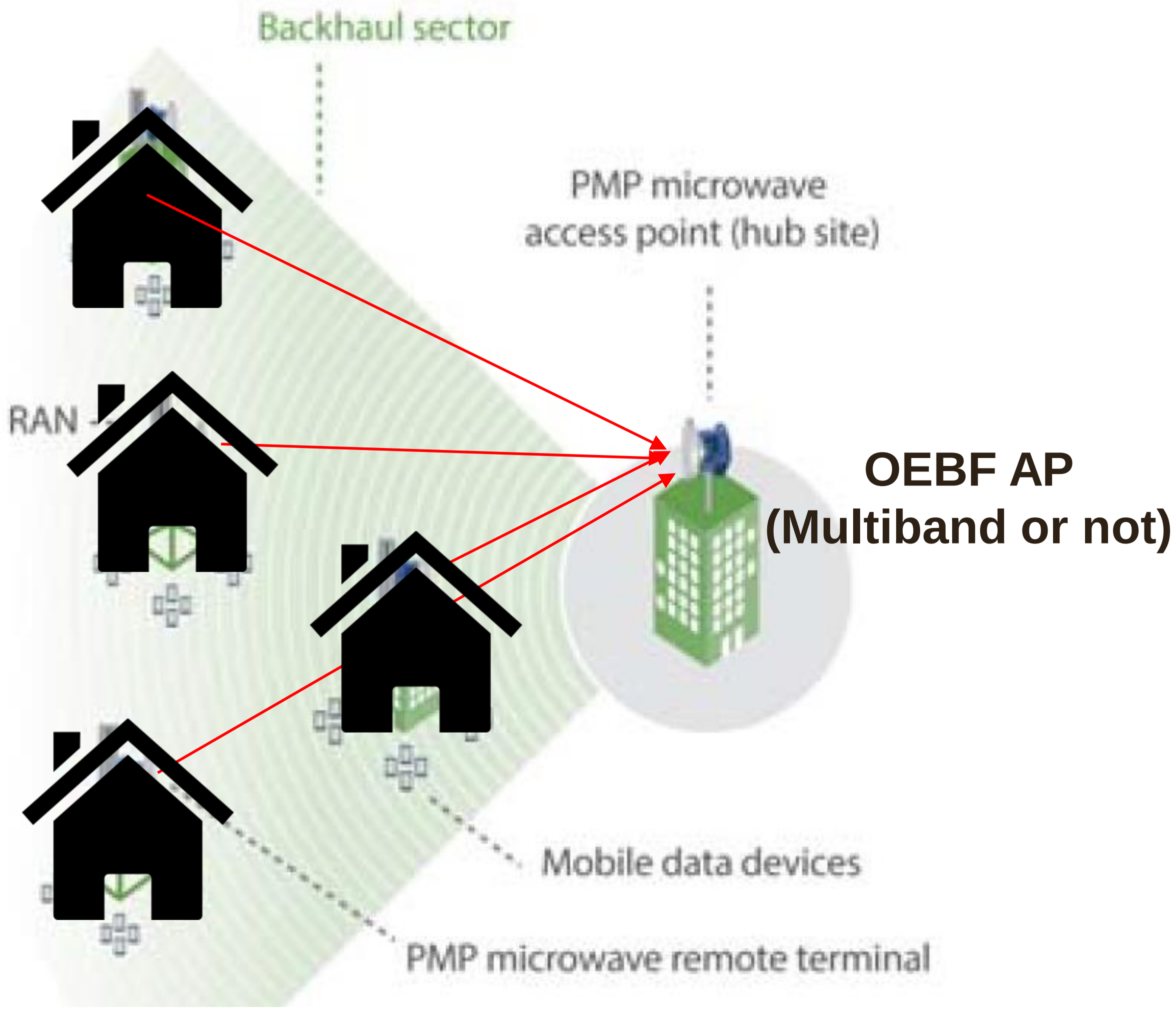
Hotspots, Drones, Front-hauling



Eindhoven University, “*ARoF-Fed Antenna Architectures for 5G Networks,*” IEEE OFC 2019.

Broadband Access (WTTx)



PMP Backhauling