Software Based Satellites
Microwave Photonic Application in New Generation of Satellites

By Mahdi Siasifar – December 12-13, 2017
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Satellite Evolution

• First Generation
  • Bent Pipe or Transparent
  • Large C and Ku Footprints

• Second Generation
  • on-board processing, regeneration and simple routing
  • Skyplex
  • Ka Spot Beams

• Third Generation
  • Re-Configuration Capabilities
  • Beam shaping Capabilities
  • User definable Capacity and Routing (day-night configuration)
  • Cellular Capacity (eg managing each 2.5 MHz instead of 36, 72 TP)
Current Ka Multi-Spot Beams

Beam 1
Beam 2
Beam 3
Beam 4
High Throughput Satellites
High Throughput Satellites (HTS)
Challenges

• Long Duration of Satellite Life Time
  • 15 years vs 2 years life time of new Networks

• Changing Regional Traffics

• Re-Configurable:
  • Beams
  • Capacity
  • Routing

• High Power requirement Applications
  • Moving Users ➔ High EIRP ➔ Multiple Spot Beams

High Power, Heavy & Expensive Satellite
Solution for Big Challenges

• Need for Innovation
• Software Based Satellite, a Paradigm Changing solution for third generation of satellites
• Pioneered by Morlete, Angeletti and their team
• A software-defined payload consists of
  • reconfigurable baseband [or intermediate frequency (IF) band]
  • digital signal processor
  • broadband analog RF platform that allow full in-orbit re-configurability of functionalities and system parameters according to the task at hand
Requirements

• Sufficient dynamic range and Bandwidth
• Covering all frequencies of the designed communication tasks
  • RF components,
  • analog-to-digital converters (ADCs),
  • digital-to-analog converters (DACs)
• Full operation in all frequencies common in the satellite
• Support the move from:
  • low-frequency C/Ku bands (4–8/12–18 GHz)
  • to high-frequency Ka (26.5–40 GHz) or Q/V bands (40–50/50–75 GHz)
Challenges & Solution

• Facing critical issues, such as:
  • Electromagnetic interference (EMI),
  • Mass,
  • Volume,
  • Complexity,
  • RF isolation,
  • power consumption Problems
  • Bandwidth

• Microwave Photonics Circuits:
  • Optical Multi-LO Generators
  • Optical Beamforming
  • Optical Switching
  • Optical Up conversion & Down Conversion
  • Optical Analog to Digital Convertors (ADC)
  • Optical Digital to Analog Convertors (DAC)
Microwave Photonics in Satellite

• European Space Agency (ESA) Started to Support it from the early 1990s,

• Great Support in past two decades by:
  • NASA,
  • the European Seventh Framework Program,
  • The China Academy of Space Technology

• Main Goal:
  • to develop novel communication satellite payloads based on microwave photonics

• Results:
  • ESA efforts led to the deployment of fiber-optic links (both digital and analog) in the Soil Moisture and Ocean Salinity observation satellite launched in 2009
Microwave Photonics in Satellite

ESA MISSIONS EXTEND FIBRE OPTICS TO ORBIT

28 April 2010
ESA’s SMOS satellite is on the verge of beginning its operational life, returning snapshots of Earth’s watery ‘skin’. The water mission’s success has been made possible by a particular technical distinction: the first mission-critical use of fibre optics.

SMOS and the Proba-2 microsatellite – which also has an optical fibre system and was launched together with the larger mission – represent a historic step forward for ‘photronics’ in space.

Two very different missions, SMOS (Soil Moisture and Ocean Salinity) and Proba-2, ESA’s latest technology demonstration satellite, shared a Rocket launcher into orbit on 2 November 2009.
Software-Defined Payloads Based on Microwave Photonics

Figure 1. A block diagram scheme of a conceptual software-defined satellite payload based on microwave photonics.
Scenario

- A satellite with $N$ user beams and broadband coverage over a certain area
- The uplink signals received by the beam shaped antenna array
- Signal amplified and converted into optical signals
- An optical multi-beamforming network allows the signals to be added in phase at designated angles to obtain $N$ signals corresponding to $N$ spot beams with a large Rx gain.
- The signals are then down-converted to the IF band at microwave photonic frequency converters driven by a multi-LO signal generated by a reconfigurable multi-LO signal generator
Scenario

• The down-converted signals are then converted into digital signals for signal processing by $N$ optical ADCs

• Due to:
  • the high sampling rate,
  • Large analog bandwidth,
  • high effective number of bits of the optical ADC

• the baseband or IF bandwidth is sufficiently large to support dynamic bandwidth allocation and direct IF digital signal processing.
Benefits & advantages of microwave photonic

• Possibility of Performing on board:
  • beam-steering,
  • filtering,
  • routing,
  • amplification,
  • allocation of power,
  • frequency, and bandwidth resources

• functions of the payload can also be freely reconfigured by upgrading the satellite software

• potentially have significantly reduced:
  • Mass,
  • Volume,
  • Power Consumption
Benefits

• The number of frequency converters can be much smaller than \( N \) by:
  • wavelength-division multiplexing (WDM) technique
  • the wide frequency tuneability of the LO generator
  • the wide operational bandwidth of the microwave photonic frequency converter (support of carrier-frequency allocation in a wide bandwidth)
Frequency Bands

- Radio
- Microwave
- Infrared
- UV
- X-ray
- Gamma ray

Visible light

Twisted pair
Coax
Maritime
AM radio
FM radio
TV
Satellite
Terrestrial microwave
Fiber optics
Tunable Optical LO Generation

- heterodyning two optical light waves at a photomixer or photodetector (PD) with a wavelength difference that falls in the microwave range
- Low noise circuits require correlated lights
- Method 1: dual-wavelength, single-longitudinal-mode laser source
  - Need for a PLL for correcting Phase Correlation
  - low-noise microwave reference needed for PLL
Tunable Optical LO Generation

• Method 2: optical frequency multiplication based on electro-optical modulators
  • High quality low frequency reference required (multiplication by 25 factor is achievable)

• Difficulties:
  • Need for higher-order nonlinearity in the electro-optical modulator for larger multiplication factor
    • drives down power efficiency,
    • raises complexity,
    • degrades spectral purity
**Tunable Optical LO Generation**

- Method 3: Optoelectronic Oscillator (OEO)
- invented by Yao and Maleki
- The $Q$ factor of the OEO cavity can easily reach the $10^6$ level, significantly reducing phase noise
- Example: 10-GHz signal with a recorded phase noise of -163 dBc/Hz at 6-kHz offset
- phase noise of the OEO is independent of the oscillation frequency,
- noise performance of the OEO does not degrade at higher frequencies
- OEO can be very compact if an ultrahigh-$Q$ whispering-gallery-mode resonator is instead of long fiber
Multi-frequency OEO

Figure 2. (a) A schematic diagram of a multifrequency OEO, with (b) the optical spectrum and (c) the electrical spectrum of the output signal [33]. ONF: optical notch filter; OC: optical coupler; EA: electrical amplifier; EC: electrical coupler.
Multi-frequency OEO

- Multi-wavelength source,
- phase modulator (PM),
- multichannel optical notch filter.
- A tunable single-passband microwave photonic filter is implemented for each optical carrier based on phase-modulation/intensity-modulation conversion.
- Once the optoelectric feedback loop is closed, multi-frequency oscillation can be obtained.
- Figure 2(b) and (c) shows the optical and electrical spectra of the output signal, respectively, when the multi-frequency OEO is configured to generate 10- and 40-GHz signals simultaneously. The oscillation frequency at each optical carrier can be adjusted independently by tuning the wavelengths of the multi-wavelength source.
- the number of output frequencies can be increased by adding more optical carriers.
Tunable Optical LO Generation

• Example: 35-GHz ultra compact OEO package smaller than a coin
• phase noise of -108 dBc/Hz at 10-kHz offset and a form factor of 0.5 x 0.5 x 0.25
• Flexible Microwave Photonic filter is incorporated
• Frequency Tunable in the oscillation loop, the OEO can be made
• For example, an OEO incorporated with a high-\(Q\) microwave photonic filter based on an externally injected Fabry–Pérot laser diode
• (LD) can generate an LO signal that is frequency tunable from 6.41 to 10.85 GHz
Optical Microwave Mixing

- optical microwave mixer Compared with its electronic counterpart shows distinct advantages in terms of:
  - Large Bandwidth
  - High Isolation
- Parallel frequency conversion can be implemented using WDM technology
- multichannel signal processing in satellite payloads
Mach–Zehnder Modulator (MZM),

Fig. 1. Silicon Mach-Zehnder modulator (MZM) with side-wall grating waveguide. (a) Top view. (b) Close-up of circled area in (a).
Mach–Zehnder Modulator (MZM),

- The most common method of implementing optical microwave mixing
- Also adopted by the ESA microwave photonic payload demonstrator
- Optical LO signal and the driven RF signal are multiplied via the Pockels electro-optic effect in the MZM
- If multiple optical LO signals are sent to the MZM, all LOs are combined with the RF signal to generate multiple IF signals at the same time.
- For example, taking advantage of the optical LOs generated by the OFC (Optical Freq. Comb), a 6.1-GHz C-Band signal can be converted to 4.1-GHz (C Band), 3.9-GHz (C Band), and 11.9-GHz (X Band) signals simultaneously.
Mach–Zehnder Modulator (MZM),

- negligible optical nonlinearity
  - large channel isolation can be guaranteed
  - optical LOs and IFs with different wavelengths do not interact

- Necessary improvements:
  - enhancing conversion efficiency, linearity, and functionality;
Photonic Frequency Mixer With Reconfigurable Functions

**Figure 3.** A schematic diagram of a reconfigurable photonic microwave mixer [41]. OF: optical filter.
Optical Microwave Mixing

• Optical microwave mixing can also be realized based on non-linear effects in nonlinear media in a semiconductor optical amplifier (SOA), such as:
  • Cross-Phase Modulation (XPM)
  • Cross-Gain Modulation (XGM) effects

• Advantages:
  • The quhybrid or monolithic integration with other devices
  • Reduce system cost considerably

• Disadvantageous:
  • quality of the converted signal is usually poor because of:
    • the complexity of nonlinear effects and the relatively
    • slow gain recovery in the SOA
Analog to Digital Convertors

• Desirable ADC:
  • fast sampling rate,
  • large analog bandwidth,
  • high Effective Number Of Bits (ENOB)

• Difficulties:
  • Degradation of the signal-to-noise/distortion ratio at high input frequencies due to aperture error in an electronic ADC
    • tradeoff between the analog bandwidth and the ENOB.
  • Limitation of sampling rate of electronic ADCs is limited by comparator ambiguity for RF signals
  • Realization of large analog bandwidth, large ENOB, and high sampling rate simultaneously
Mode-locked Laser (MLL)

- **Mode-locking** is a technique in optics by which a laser can be made to produce pulses of light of extremely short duration, on the order of picoseconds ($10^{-12}$ s) or femtoseconds ($10^{-15}$ s).
- Pulse Train is used for Sampling
- MLL pulses has:
  - Ultra-low timing
  - Ultra low jitter
  - Ultra-narrow
- Results in:
  - Low Aperture error
  - Steep Suppression of corresponding noise
Time stretch analog-to-digital converter
Typical Structures Of An Optical ADC (1)
Typical Structures Of An Optical ADC (2)
Typical Structures Of An Optical ADC (3)

Figure 4. Several basic structures of an optical ADC, in which the optical technique plays the role of (a) sampling, (b) digitization, and (c) signal stretching [44], [49]. EO: electro-optical.
Current Technology of Optical ADC

• Using distributed Raman optical amplification:
  • 10 TSa/s equivalent sampling was demonstrated
  • stretch factor up to 250
Optical Digital-to-Analog Conversion

• A high-speed DAC converts processed digital signals back to the analog domain.
• optical techniques can increase the clock speed by more than one order of magnitude compared with electronic solutions,
• DAC realized using the optical approach can achieve high speed and high resolution.
• Many photonic DACs have been proposed in the past few years, divisible into three main categories:
  • Parallel-Weighted DACS (12.5-GSa/s Achieved)
  • Serial-Weighted DACS (40 GSa/s Achieved)
  • Pattern-recognition-based DACS (40-Gbit/s 2-bit optical DAC)
Parallel Weighted Structure

Figure 5. A schematic diagram of a typical parallel-weighted DAC [51]. LPF: low-pass filter; LSB: least significant bit; MSB: most significant bit.
Optical Digital-to-Analog Conversion serial-weighted structure

Figure 6. A schematic diagram of a typical serial-weighted DAC [54]. AC: amplitude controller.
Phase-Array Beamforming
Optical Beamforming

• Beamforming Network Systems:
  1. Phase-shifter–based
     • relatively mature in the electrical domain
  2. True-time-delay–based

• Optical Phase Shifter Based distinct features:
  • Small size,
  • low weight,
  • low transmission loss,
  • large frequency range,
  • Immunity to EMI
Phase Shifter Based Optical Beamforming Networks (OBFNs)

- Programmable Photonic Processor
  - consisted of a two-dimensional array of liquid crystal-on-silicon pixels:
    - manipulated both phase and amplitude of the optical carrier
    - and the sideband an optical single-sideband (OSSB) signal

- Key Advantages
  - Scalability to form a large number of elements
  - Flexibility to control by software
  - Simultaneous Peak and Null forming (Anti-Interference!)
Optical Beamforming using Polarization Modulation

- Figure 7. Experimental setup of an OBFN based on polarization modulation
  VNA: vector network analyzer.
- PolM: polarization modulator;
- OBPF: optical bandpass filter;
- PC: polarization controller;
- PBS: polarization beam splitter;
- EDFA: Erbium-doped fiber amplifier.
Difficulties with phase shifter-based OBFNs

- The main limitation is the beam-squint effect
- the beam direction changes according to the RF signal frequency in wideband signals
- Future software-defined payloads must be capable of bandwidth allocation,
  - wideband beamforming is essential to manage bandwidth variation in the beams.
- 3-GHz bandwidth in case of Ka-Band allocated to one single-spot beam
True-Time-Delay–Based Optical Beamforming

• OBFNs based on true time delay (TTD) To realize wideband beamforming, were proposed and first demonstrated in 1991 using optical fiber as the TTD module

• TTD-based OBFNs can also be implemented using:
  • fiber Bragg gratings (FBGs),
  • fiber-optic delay line matrices,
  • slow light
  • on-chip ring resonators
**True-Time-Delay–Based Optical Beamforming**

- A schematic diagram of a multi-beam OBFN based on programmable TTD and microwave photonic filters efficient at both the Tx and Rx modes

- consisting of:
  - a shared OFC generator,
  - shared multi-frequency RF source,
  - a number of antenna elements connected to separated TTD modules,
  - several shared RF receivers,
  - and a controlling subsystem
True-Time-Delay–Based Optical Beamforming

Figure 8. A schematic diagram of a multibeam OBFN system based on programmable TTD and microwave photonic filters [77]. MFP: microwave photonic filter.
Satellite Payload Requirements
Result

• OBFN system capable of steering multiple independent beams simultaneously, effective in both Tx and Rx modes, is fully realized.
Optical Switching

• RF switches are utilized in satellite payloads to realize signal routing, function switching, and system reconfiguration

• Optical techniques are beneficial in terms of wide working bandwidth and immunity to EMI,

• Stable switching of high-definition (HD) video signals with 1.5-GHz bandwidth was successfully realized

• Two HD video signals are up-converted to Ku Band (16 GHz) and transmitted separately to the free space through two antennas, emulating two transmitters at the Earth station
Satellite Payload Requirements
Discussion and Conclusion

• recent developments in microwave photonics for potential application in satellite payloads was discussed
• Different modules are realizable by Microwave Photonics
• the majority of microwave photonic techniques are still relatively unsophisticated and are future of Satellite Payloads
• current trend, where more microwave photonic modules are applied in satellite payloads, is irrefutable and irreversible
• Optical LO generation and distribution has already been employed successfully, and, hopefully, optical microwave mixers and optical switches will be deployed in space in the near future with the rapid development of integrated microwave photonics
Discussion and Conclusion

• [1] Satellite Payloads Pay off, Shilong Pan, Dan Zhu, Shifeng Liu, Kun Xu, Yitang Dai, Tianliang Wang, Jianguo Liu, Ninghua Zhu, Yong Xue, and Naijin Liu, IEEE microwave magazine, September 2015

• All 85 references in [1]
Questions?