Optical Free Space in Time-Sensitive Networks

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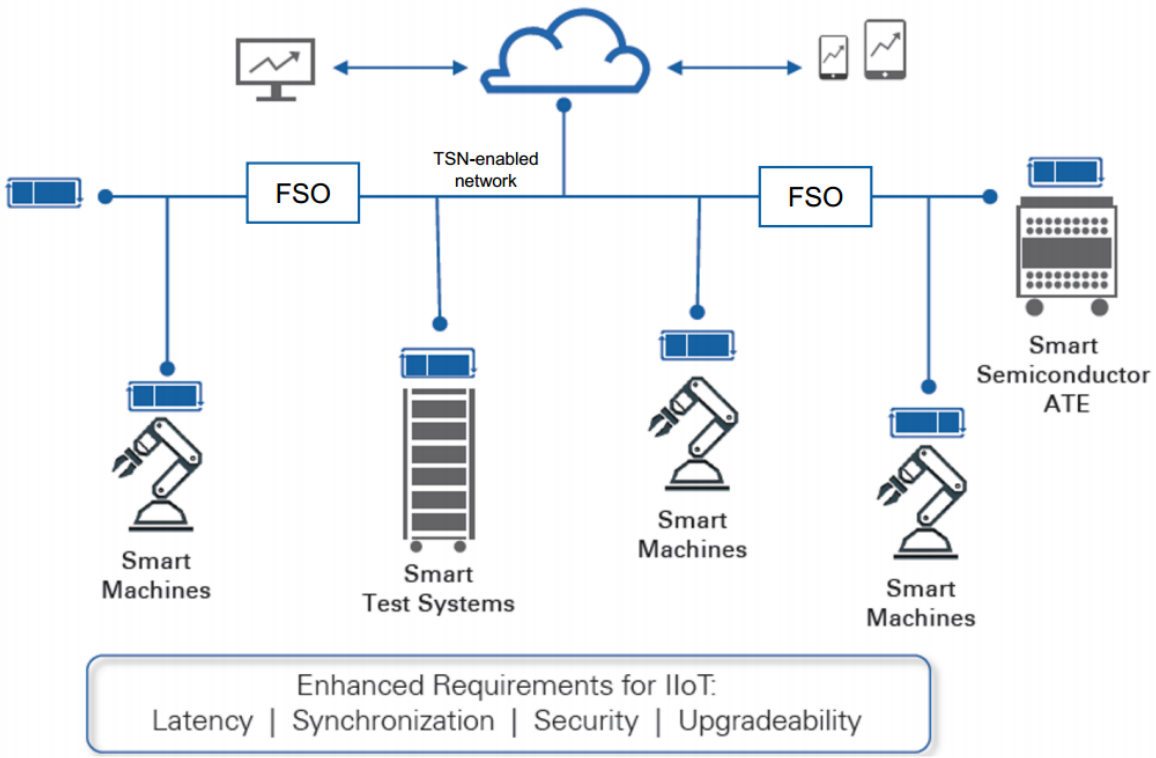
Motivations – Advanced Manufacturing

- Adoption of embedded systems and robotics that collectively work as part of a larger system, where each node works as an "agent" that handles different types of data (voltage, current, sound, image, …) in multiple domains (temporal, spatial, spectral, …)
  - Data intensive algorithms are being implemented (e.g., Machine Learning, Deep Learning) in the industrial environment, supported by the Cloud (remote)
- New technologies are being adopted, e.g. Virtual Reality-VR and Augmented Reality-AR, Industrial Internet of Things-IIoT
- Combination of **high throughput** data streaming between devices and systems, with a **tight synchronization** between them
  - The use of high-speed networks (10 GbE) and wireless communications (e.g., Wi-Fi) is becoming common on the factory floor
    - Ex. TB of video and images to support operators on the factory floor using VR and/or AR for maintenance and in need to consult technical manuals on site
  - Closed-loop responses in the milli-seconds (ms):
    - Ex. close loop control of robotic arm that responds to human command
  - Low-jitter (deterministic) communications:
    - Ex. Micro-second (us) jitter in communications between robots working in tandem and in synchronization
- **Electrical noise** (EMI) affects the communications/networking infrastructure on the factory floor and limits adoption of new technologies

FSO & Time-Sensitive Networks in Advanced Manufacturing

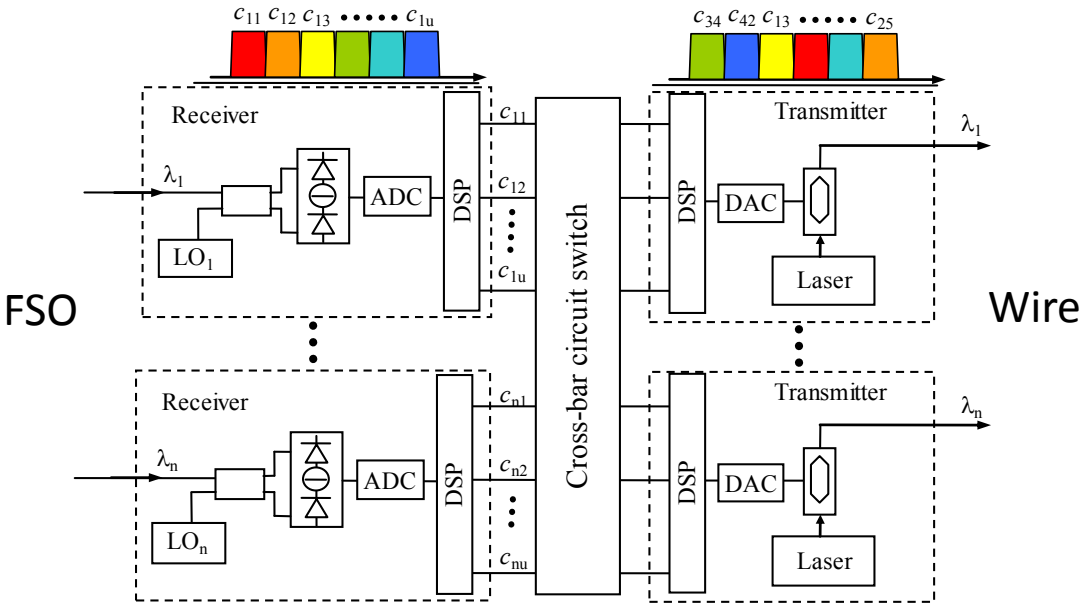


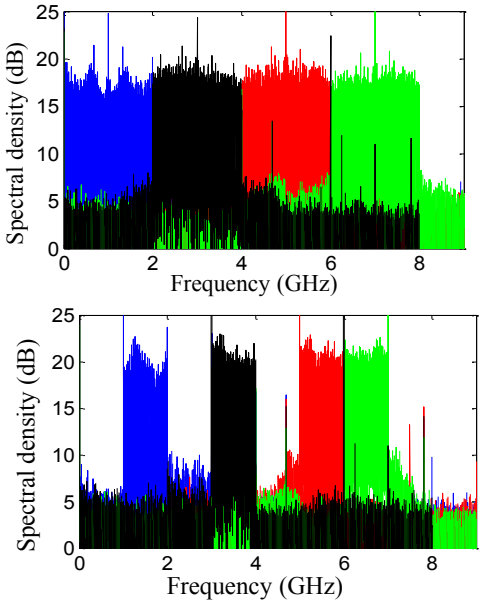
IEEE Standards and WGs on TSN

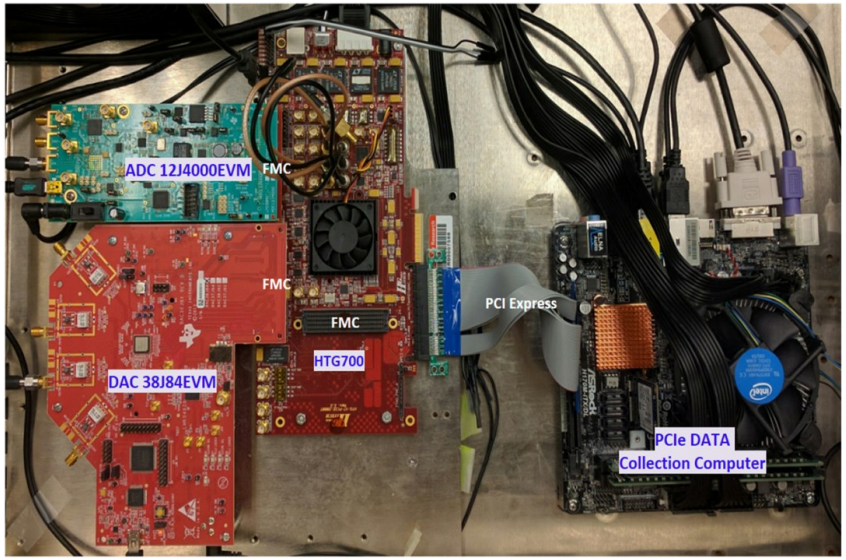
- Time Synchronization:
  - IEEE 802.1AS, IEEE 1588
- Traffic Scheduling:
  - IEEE 802.1Qbv
- System Configuration:
  - IEEE 802.1Qcc

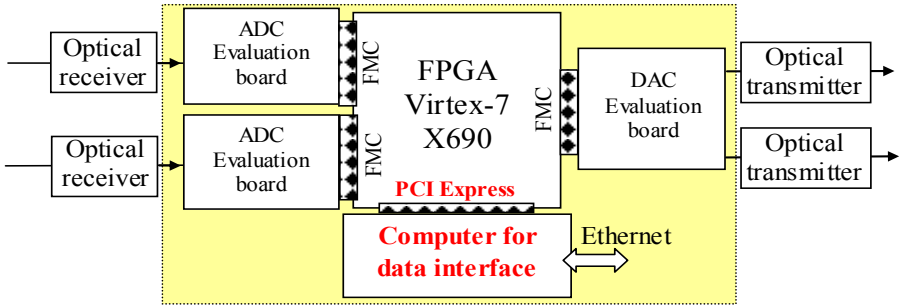
- Copper and fiber are not sufficient for the rapid implementation of high-speed networks, while leveraging any existing Ethernet and/or Wi-Fi networks
- Free Space Optics (FSO)-assisted networks are becoming more and more appealing as a viable low-cost, high-rate alternative to copper and fiber
- **Reliability and deterministic response** are both critical in most of these implementations, requiring provisions for tight synchronization between devices and machines
- Typically, a FSO link quality depends on such factors as power, distance, and weather conditions - for industrial implementation, deterministic response is also important

Deterministic E2E Latency through Digital Subcarrier Multiplexing

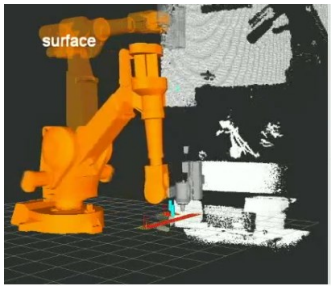




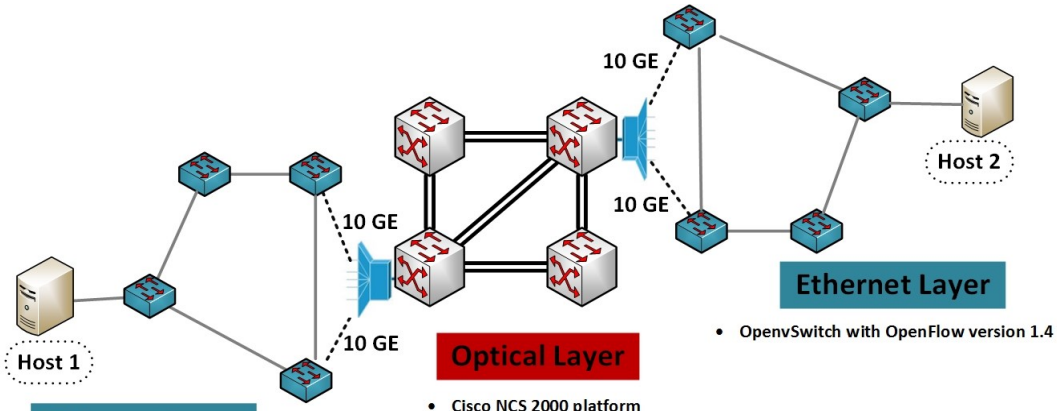




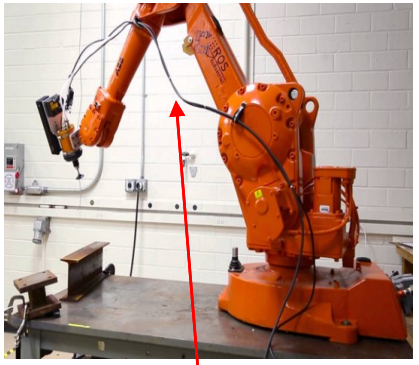
Reliability through Orchestration of Network Resources & Robots



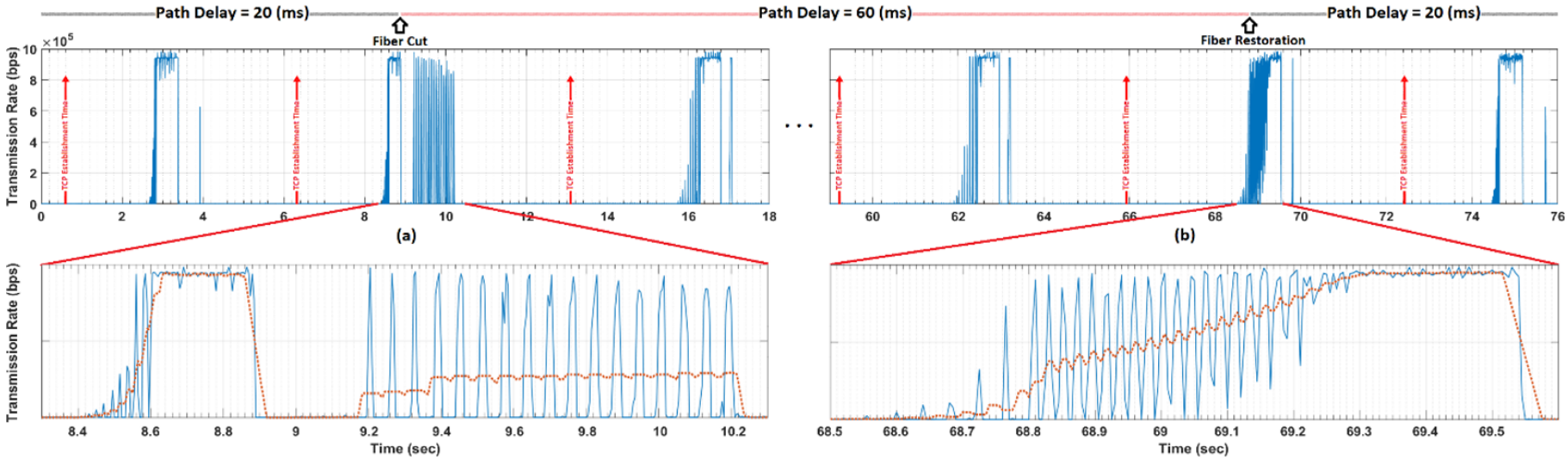
Programmable Optical Network (PROnet) Test-bed



- OpenvSwitch with OpenFlow version 1.4
- Cisco NCS 2000 platform
- "CDC" ROADM architecture
- 100G coherent network
- OpenvSwitch with OpenFlow version 1.4



Cables!!!



TCP data transfer rate for 3 Kinect images (each about 60MB) as required by the Godel application

Challenges

- Unpredictable signal fading and multipath
- Robust beam steering
- FSO-wire seamless and time-sensitive data transfer
- Robot movements
- Obstacles
- Noise sources

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