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Converged Wireline and Wireless Access Over a 78-km Deployed Fiber Long-Reach WDM PON

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***Abstract*—In this letter, we demonstrate a 78.8-km wavelength-division-multiplexing passive optical network supporting converged transport of 21.4-Gb/s nonreturn-to-zero differential quadrature phase-shift keying, optical phase-modulated 5-GHz radio-over-fiber, fiber and air transmission of 3.125-Gb/s pulse ultrawideband, and 256-quadratic-amplitude modulation wireless interoperability for microwave access.**

***Index Terms*—Coherent optical systems, converged access networks, ultrawideband (UWB) signaling, wireless interoperability for microwave access (WiMAX).**

I. Introduction

HYBRID optical/wireless access network architectures are considered a promising solution for large-scale deployment of broadband access as they combine the advantages of high capacity offered by optical access with the flexibility provided by wireless networks [1], [2]. Simultaneous transport of wireline and wireless types of signals, fulfilling power budget, dispersion, and other quality requirements for both signal types, over a common fiber infrastructure is an important aspect for hybrid optical wireless access networks.

We report on a converged wireless and wireline, wavelength-division multiplexing (WDM) passive optical network (PON) access link over a 78.8-km-long commercially deployed optical fiber in Copenhagen. We successfully implemented an eight-channel, single-fiber, WDM transmission system simultaneously supporting 85.6-Gb/s baseband via four 21.4-Gb/s nonreturn-to-zero (NRZ) differential quadrature phase-shift keying (DQPSK) channels, 500 Mb/s via two coherently detected phase-modulated radio-over-fiber (RoF) channels, 3.125 Gb/s via impulse radio ultrawideband (UWB), and intensity-modulated, direct-detected RoF link with quadratic-amplitude modulation (QAM) at 12 megabaud (MBd). Air transmission was demonstrated after fiber transmission for the UWB and WiMAX signals.

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II. System Layout

Fig. 1 shows a block diagram of the field trial and setup used in the experiment. The field-deployed fiber connects the Kongens Lyngby campus of the Technical University of Denmark (DTU) and facilities located in the suburb of Taastrup. The fiber is a G.652 standard single-mode fiber (SMF) type (16.5 ps/nm·km chromatic dispersion, 0.20 dB/km attenuation, polarization dispersion coefficient < 0.20 ps/$\sqrt{\text{km}}$). The total link loss was measured at 25 dB. The eight WDM channels employed were separated by 200 GHz, at standard International Telecommunication Union (ITU) wavelengths, denoted by $\lambda_1 = 1549.3$ nm through $\lambda_8 = 1560.0$ nm. Four wavelengths (λ_{5-8}) were used for NRZ-DQPSK: two $(\lambda_{2,4})$ for coherent RoF, λ_3 for UWB, and λ_1 for WiMAX. Launch power into the deployed fiber was set to 0 dBm for each of the eight channels. A dispersion-compensating fiber (DCF) was used at the transmitter; this also ensured decorrelated signals at the input to the transmission fiber. A preamplifier erbium-doped fiber amplifier (EDFA) overcame transmission losses before wavelength demultiplexing by arrayed waveguide grating (AWG). AWG spacing of 200 GHz was used due to equipment availability; we anticipate good system performance with closer spacing [3].

A. NRZ-DQPSK Baseband

The transmitter setup comprises four DFB lasers at wavelengths $\lambda_5 - \lambda_8$ multiplexed in an AWG and NRZ-DQPSK modulated using an inphase/quadrature (I/Q) modulator driven by two electrical pseudorandom bit sequences (PRBSs) of length $2^7 - 1$ bits and bit rate 10.7 Gb/s, resulting in a per-channel bit rate of 21.4 Gb/s at a symbol rate of 10.7 GBd. The $2^7 - 1$ bit pattern length was selected due to limitations of the bit error rate tester (BERT) functionality. Since we used phase modulation, no pattern dependency was expected from nonlinear effects in the transmission fiber. After transmission and wavelength demultiplexing, the NRZ-DQPSK signals were demodulated using a one-symbol delay Mach–Zehnder interferometer (MZI) and detected by a pair of balanced photodetectors (BPDs). The BER of each DQPSK tributary was measured independently, and we report the average obtained.

B. Coherent RoF

A 5-GHz RF carrier at $+8$ dBm was BPSK modulated at 250 Mb/s, and used to optically phase modulate signals at wavelengths of λ_2 and λ_4. At the receiver, the desired channel was optically mixed with a continuous-wave local oscillator (LO) signal, derived from a tunable laser source at 0 dBm output power, and coherently detected using a 90° optical hybrid with integrated photodetectors. The in-phase (I) and quadrature (Q)

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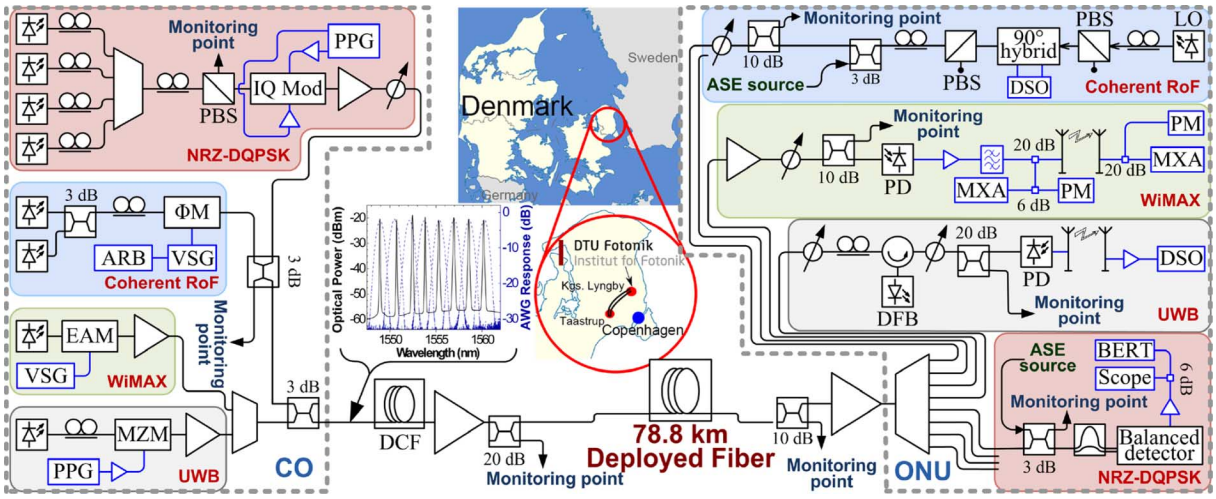

Fig. 1. Detail of the experimental setup. PPG: pulse pattern generator; PBS: polarization beam splitter; PM: optical phase modulator; ARB: arbitrary waveform generator; VOA: variable optical attenuator. ASE added to evaluate system OSNR sensitivity for phase-modulated signals: precompensating DCF-implemented decorrelation of RoF and NRZ-DQPSK signals. (Inset) Spectra of launched WDM optical signal (solid line) and AWG response (dashed line).

electrical signals were sampled at 40 GSa/s by a sampling oscilloscope (SO) with a 13 GHz bandwidth. The stored signals were processed offline using DSP algorithms described in [3] to perform signal demodulation and BER evaluation.

C. Impulse Radio UWB

A lightwave at λ_3 (1552.80 nm wavelength) was modulated by a 12.5-Gb/s pattern "1000" using a Mach–Zehnder modulator (MZM). An uncooled DFB laser was optically injected with the incoming signal from the fiber link. Under optical injection, cross-gain modulation and relaxation oscillations governing the dynamic response of the DFB shape its output signal [4]. The incoherent combination of the injected and DFB wavelengths after photodetection generated a pulse with a postdetection RF spectrum that is compliant with the impulse radio UWB mask. Air transmission of 40 cm was implemented. These UWB signals were sampled by a 40 GSa/s sampling scope with 13 GHz bandwidth, and processed offline using a DSP algorithm.

D. WiMAX

An electroabsorption modulator (EAM) fed by an optical carrier at λ_2 was modulated with a 256-QAM RF signal, centered at 5.8 GHz, obtained from an Agilent E4438C vector signal generator (VSG); a boost EDFA and a variable optical attenuator (VOA) controlled the launch power. A preamplified receiver was implemented with a 30-dB gain EDFA, an optical bandpass filter (BPF), and a 10-GHz PIN photodiode. The electrical signal obtained was amplified by 35 dB, filtered by 25 MHz RF duplexers for 5 GHz unlicensed ISM band operation, and radiated by a 12 dBi omnidirectional 5 GHz antenna. The wireless signal was detected with an identical antenna at 40 cm separation, and amplified and assessed with an Agilent 9020 MXA vector signal analyzer (VSA) with the 89 600 VSA signal analyzer software. We report error vector magnitude (EVM) sensitivity to RF source power at both ends of the wireless link for the single active wavelength and for all WDM transmitters active. We additionally assessed the performance with extra 40 km of uncompensated SMF, after DF and preamp and the postdetection eye diagram.

III. Results

A. NRZ-DQPSK Baseband

The BER of the four NRZ-DQPSK-modulated baseband channels back-to-back (B2B) and after fiber transmission is plotted in Fig. 2(a) with filled symbols/solid lines for the back-to-back case and hollow symbols/dashed lines for the transmitted. OSNR requirement for a BER of 10^{-9} was observed between 22 dB (λ_5) and 23.3 dB for λ_8. At λ_7, a penalty of 0.3 dB was observed after transmission; for all other channels, no penalty was measured. The eye diagrams before and after transmission shown in Fig. 2(b) show no transmission distortion, thus confirming good transmission properties.

B. Coherent RoF

A 250-MBd BPSK data signal modulating a 5-GHz RF carrier for each WDM channel was successfully recovered after transmission through the dark fiber with input power to the coherent receiver set to -15.77 and -16.77 dBm, respectively. In Fig. 2(b), the BER curves for back-to-back and after fiber transmission are computed as a function of OSNR values from 7 to 12 dB. We observed a receiver sensitivity penalty of 0.5 dB at λ_2 for BER at 10^{-3}, whereas a 2 dB penalty was observed in channel 4, which we believe was caused by partial misalignment of the source with the AWG passband.

C. Impulse Radio UWB

We generated 3.125-Gb/s ON–OFF key (OOK) modulation with $2^7 - 1$ PRBS; an example of "1110111" pattern and the resulting RF spectrum are shown in Fig. 3(a). The frequency spectra observed are compatible with the FCC (indoor) UWB mask. We used a sample size of 684 kilosamples, and a DSP algorithm was employed to calculate the BER offline. From the BER measurement curves, we observed less than 0.5 dB penalty between B2B and fiber transmission (for both single-channel and WDM transmissions).

D. WiMAX

We successfully transported 256-QAM signals at 12 MBd over the deployed fiber and an additional 40 km SMF with no

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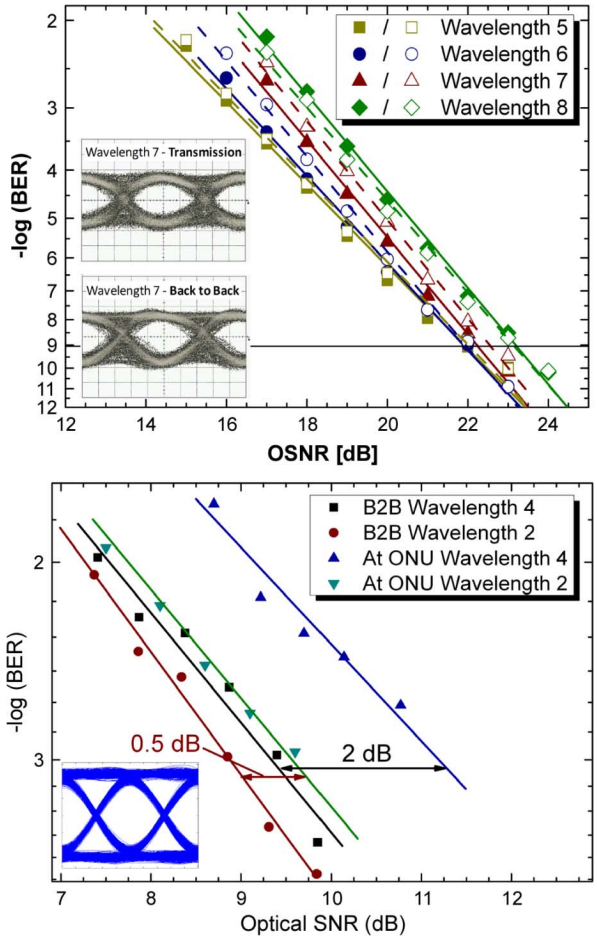

Fig. 2. BER results. (Top) 21.4-Gb/s NRZ-DQPSK. (Bottom) Coherent RoF. Sample eye diagrams are also shown.

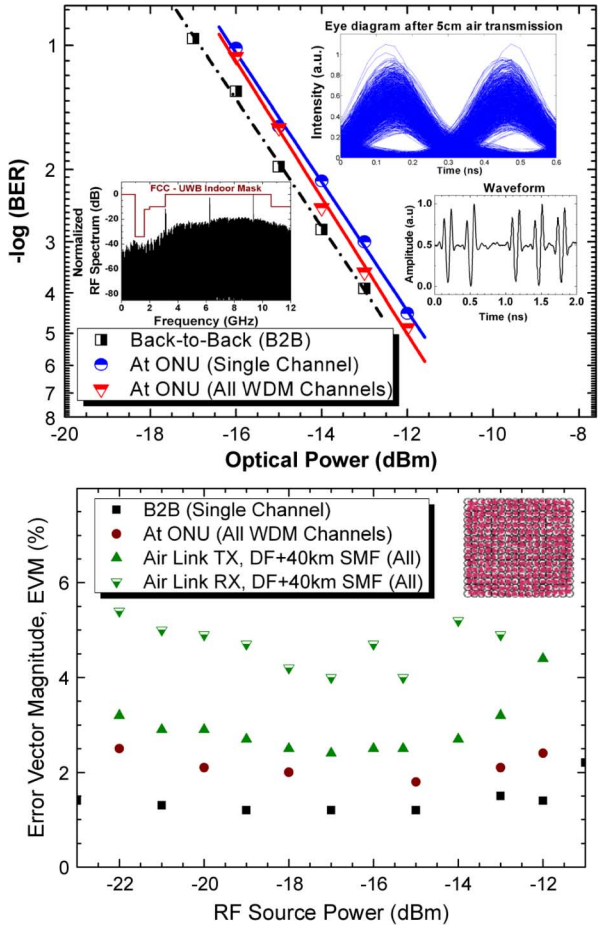

Fig. 3. (Top) BER results, RF spectrum, and eye diagrams obtained for 3.125-Gb/s UWB. (Bottom) WiMAX EVM sensitivity and constellation.

further optical amplification, with below 3% EVM at the remote transmit antenna, as shown in Fig. 3(b). System spur-free dynamic range was 74 dB/Hz$^{2/3}$.

IV. Conclusion

We successfully demonstrated combined transport over a single 78.8-km field-installed fiber of NRZ-DQPSK-modulated baseband access at 21.4 Gb/s per channel, coherent RoF at 250 Mb/s per channel, impulse-radio UWB at a record speed of 3.2 Gb/s, and a 256-QAM WiMAX signal at 12 MBd. For the UWB and WiMAX signals, air transmission was included after the fiber link. This is the first known demonstration of its kind, and it proves that the existing standard SMF based fiber infrastructure can support the seamless coexistence of various wireless and wireline signals for future converged broadband access networks. Prior results [5] also suggest the feasibility of WDM transmission with 100-GHz channel separation.

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