Overcoming the challenges of very high-speed optical transmission

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Over the past 15 years, the capacity of optical fiber transmission systems has risen by more than three orders of magnitude. At the same time, the maximum achievable distance for a single link is 10 times greater than what it was over a decade ago. Innovative optical technology has resulted in a significant drop in the cost-per-bit for transport. Essentially, operators want this cost to continue to fall, as this will help them to meet the constantly growing demand for bandwidth.

However, this approach is limited when it comes to achieving channel bitrates over 10Gbps, due to the cost of high-speed electronic devices, and the complexity in mitigating fiber propagation impairments. So, in a manner similar to developments made in wireless communications, intensity modulation in optical fiber has been replaced by complex multilevel modulation formats. With the addition of inline polarization, the symbol rate decreased even further, and coherent detection was added to compensate for propagation impairments in the digital domain.

Current 40Gbps and 100Gbps DWDM systems use DP-QPSK as a modulation format, but with the arrival of 400Gbps and 1Tbps DWDM channels, the race for higher transmission speeds is on. Such rates pose new challenges that are extremely difficult to overcome, so much so that high-speed transmission capabilities are a benchmark of technology leadership.

**Terms and abbreviations**

- ADC: analog-to-digital converter
- BCJR: Bahl Cocke Jelinek Raviv
- CNIT: Consorzio Nazionale Interuniversitario per le Telecomunicazioni
- DP-16QAM: dual polarization 16QAM
- DP-QPSK: dual-polarization quadrature phase shift keying
- DSP: digital signal processing
- DWDM: dense wavelength division multiplexing
- FEC: forward error correction
- FFE: Feed Forward Equalizer
- ICI: inter-carrier interference
- ISI: inter-symbolic interference
- LDPC: low-density parity check
- MAP: maximum a posteriori
- MI: mutual information
- MIMO: multiple input, multiple output
- OFDM: orthogonal frequency division multiplexing
- OSNR: optical signal-to-noise ratio
- PAR: peak-to-average ratio
- PDM: polarization division multiplexed
- PMD: polarization mode dispersion
- QAM: quadrature amplitude modulation
- QPSK: quadrature phase shift keying
- ROADM: reconfigurable add-drop multiplexer
- SC: subcarrier multiplexing
- SDN: software-defined networking
- SE: spectral efficiency
- TFP: time-frequency packing
- WDM: wavelength division multiplexing
- WSS: Wavelength Selective Switch

Applying intensity modulation (a relatively simple transmission scheme compared with those of modern radio systems) in spectral direct-detection systems is one method that has been used to increase network capacity. This method uses dense wavelength division multiplexing (DWDM) and optical amplification, to achieve capacities as high as 800Gbps on a single fiber, corresponding to 80x10Gbps DWDM channels, over link distances of up to 3,000km without the need for signal regeneration.
One way around this problem in a radio environment is to use frequency multiplexing because this approach lowers the constellation size and symbol rate, and can support 400Gbps and 1Tbps transmission rates. However, applying the same techniques successfully used in radio to optical communication is not always straightforward. OFDM, for example, is an encoding method that is widely used in radio systems, but its application to optical communications is much more complex.

For optical to reach the desired transmission rates, a number of things need to be in place: accurate high-speed analog-to-digital converters (ADCs) are required; the optical carriers need to be phase synchronized; a long cyclic prefix overhead is needed to compensate for chromatic dispersion; fiber sensitivity to phase noise needs to be accounted for, as do the nonlinear effects that result from high peak-to-average ratio (PAR).

The solution usually adopted in fiber systems is Nyquist-WDM, subcarrier multiplexing (SCM) that is spectrally efficient, where modulated carriers are first filtered close to the Nyquist bandwidth – half the symbol rate – and then densely frequency multiplexed with the help of steep electrical or optical filters to prevent inter-carrier interference (ICI) from intensifying.

As an example, 2.24Tbps can be transmitted on 375GHz bandwidth using 10xDP-16QAM-modulated carriers, giving an SE of 5.97bps/Hz – almost three times the 2bps/Hz provided by 100Gbps systems. However, there are at least two reasons why Nyquist-WDM is not the ultimate solution for high-speed transmission:

- it is incompatible with installed ROADMs that support 50GHz-spaced optical channels (in accordance with the ITU-T standard); and
- it is incompatible with many of the installed DWDM links on account of its low tolerance-to-noise ratio and nonlinear effects.

Is it possible to overcome these issues and satisfy operator requirements to carry out capacity upgrades on their networks in a seamless way? This is the challenge the Ericsson Research team in Pisa, Italy has taken on together with its local academic partners Scuola Superiore Sant’Anna and CNIT.

**The Ericsson approach: time-frequency-packing modulation**

Orthogonal signaling is the usual method to maximize spectrum usage for both radio and optical communications, as it removes both ISI and ICI. The maximum spectral efficiency possible with orthogonal signaling is SE = log2M, where M is the number of constellation symbols. So, it appears that good spectral efficiency is only achievable with large constellations – and these do not work in optical links. But is this really the case?

Consider a scenario where multiple carriers are spaced in frequency by F, each employing an M-ary modulation format with a symbol interval of T. By relaxing the orthogonality condition (FT < 1), SE can be increased – without increasing M, and by acting on F and T instead. From information theory, we get SE = MI/(FT), where MI is the mutual information between transmitter and receiver and is a decreasing function of FT. This guarantees that a maximum value exists for SE, which is illustrated in Figure 1.

Faster-than-Nyquist signaling is an example of non-orthogonal transmission and involves sending time and frequency overlapping pulse trains. The optimal values of F and T are the smallest values that guarantee the minimum distance between the constellation symbols is equal to the Nyquist case. However, the complexity of the receiver quickly becomes unmanageable when this approach is used.

In the Ericsson approach SE is maximized once receiver complexity has been fixed through design. Implementing the TFP concept in practice can be achieved by applying narrow filtering, with a bandwidth that is much lower than the Nyquist one, and an LDPC-encoded QPSK signal – which is easier to generate and more resilient to noise than 16QAM. The lower bandwidth of this approach allows F to be reduced, which ultimately increases spectral efficiency.

Frequency overlapping was not used in the practical implementation of TFP in an Ericsson-Telstra field trial (which is described later in this article). Instead, each carrier was individually sampled and processed.

While such an implementation is a sub-optimal one, an additional increase in SE is possible using channel shortening and by applying multi-channel receiver techniques. As illustrated in Figure 2 (see over) the distortion introduced by the transmission filter at the receiver is recovered by digital signal processing (DSP) – an adaptive equalizer processes the signals received on two orthogonal states of polarization to compensate for fiberchromatic and polarization-mode dispersion; the equalizer output is then input to a BCJR detector, which iteratively exchanges information with an LDPC decoder until the correct code word is detected.
The total aggregate bitrate of 1.12Tbps was obtained by eight optical carriers, each modulated by a 140Gbps narrow filtered DP-QPSK signal, corresponding to 35Gbaud. The baseband filtering bandwidth was 10GHz – which is much lower than the Nyquist-WDM value.

Although it is not required by the TFP modulation format, the carriers were unequally spaced so that a pair of them could be allocated to each ROADM frequency slot (as illustrated in Figure 3B). The system exploited different LDPC codes to balance net SE with error-correction capability, providing a way to implement an adaptive optical interface without having to change modulation format – the more traditional solution.

To finely adjust the transmitted capacity to the propagation conditions, the system could be configured with six different code rates (9/10, 8/9, 5/6, 4/5, 3/4 and 2/3), depending on accumulated OSNR and propagation penalties. This technique is more accurate and less hardware demanding than 16QAM-to-QPSK modulation switching, which always requires a halving of the transmission capacity.

**Receiver structure**

For each carrier, the receiver uses a conventional polarization-diversity optical front end, in which the incoming signal and local oscillator are first split into two orthogonal polarization states and then combined separately. Local oscillator frequency and phase are not locked to the frequency and phase of the signal, and any difference is compensated for by DSP, which can recover any practical value of frequency offset in the order of 1GHz.

The output of the front end, the photo-detected signals of four balanced photodiodes (two for each polarization), is sampled and then digitally processed. No chromatic dispersion compensation is performed along the link, so the accumulated dispersion, of about 17,000ps/nm/km, is entirely compensated for by a frequency domain
equalizer, and then by an adaptive FFE – which accounts for other linear impairments, such as polarization rotation, residual dispersion and polarization mode dispersion. The equalizer output feeds four parallel 4-state BCJR detectors followed by four LDPC decoders. The BCJR and LDPC blocks iteratively exchange information, for a maximum of 20 iterations, to achieve MAP detection according to the turbo-equalization principle.

Field trial results

Figure 4A illustrates the measured ROADM amplitude transfer function and SE within each ROADM frequency slot for three cases:
1. 1Tbps channel alone;
2. 1Tbps channel with 800GHz spaced adjacent channel;
3. 100GHz spaced 40Gbps and 100Gbps co-propagating channels.

SE is defined as the ratio between the maximum net bitrate (not including FEC overhead) that ensures error-free operation and the ROADM bandwidth. Figure 4B shows the resulting SE values, obtained by optimizing the code rate individually for each carrier.

There is no appreciable difference in performance among the three cases, which implies that the interference between the 1Tbps channel and neighboring channels, with lower bitrates, is negligible. Similarly, no penalty was measured on either the 40Gbps or 100Gbps channel due to the presence of the 1Tbps channel.

To put pressure on the system, the polarization mode dispersion (PMD) was increased by means of a PMD emulator. No SE variation was detected up to 170ps of additional differential group delay, and a 5 percent drop was observed with a delay of 200ps. These are excellent results given that the maximum group delay expected in a 3,000km link is about 50ps.

To further test the stability of the solution, measurements were taken every 15 minutes during a 24-hour period, and no difference was detected in the overall performance.

By varying the carrier power (using a code rate of 5/6 for all the sub-channels), the resilience of fiber to non-linear propagation was also tested during the field trial. An optimal sub-channel power of about -1dBm was found to minimize the non-linear propagation penalty, and a maximum OSNR penalty of 1.3dB was obtained with a power range between -3dBm and 1dBm – demonstrating that TFP can cope with typical system tolerances, such as those due to gain flatness of the optical amplifiers.

Taking the optimized carrier power as -1dBm, the received OSNR with 0.1nm resolution bandwidth varies between 15dB and 1dB along the carriers – a value that is compatible with the majority of installed DWDM links.

Conclusions

The field trial demonstrates the suitability of the TFP approach to meet operator demand for high-capacity upgrade of DWDM networks. The proof points provided by the field trial show that the long-haul distances of the 1Tbps system are comparable with that of a 100Gbps system. The 1Tbps system, however, provides three times the spectral efficiency, is compatible with 50GHz ITU-T frequency grid and installed ROADMs, it can coexist with installed 40Gbps and 100Gbps channels, it provides stable operation over time, and is robust with respect to system and fiber tolerances.
Although the focus of the field was on 1Tbps transmission, the modularity of the TFP solution makes it adaptable for 400Gbps. A straightforward method of four carriers instead of eight can be used together with channel shortening and multichannel detection techniques to improve the spectral efficiency dramatically. This adaptation is important given that 400Gbps optical interfaces for metro and regional distances, based on 16QAM, are the current focus of standardization work.

But a solution for long haul, with link distances greater than 500km, has yet to be found, and TFP can play a key role in providing one. 400Gbps capabilities are being introduced in SSR and SPO product families, enabling high-speed connectivity between routers in next-generation IP over WDM and ultra-high capacity packet optical transport.

In addition, the capability of TFP to finely adjust the throughput on a per carrier basis works well with concept of SDN – where bandwidth resources need to be rerouted easily according to new service demands or dynamic changes of the traffic load – as is required by data center virtualization.

Beyond the technical result, the field trial was a good example of an agile and informal working environment, where researchers from industry and academia came together, exchanged ideas, and encouraged unconventional thinking to create an innovative solution.

References
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