Comparison of three coherence multiplex system topologies

Arjan Meijerink, Robert Taniman, Geert Heideman and Wim van Etten

University of Twente, Department of Electrical Engineering, Telecommunication Engineering Group,
P.O. Box 217, 7500 AE Enschede, The Netherlands
a.meijerink@ieee.org

Coherence multiplexing (CM) is a potentially inexpensive form of optical CDMA, which is particularly suitable for optical access networks or LANs. Various system topologies are known for achieving multiplexing of several CM channels over one optical fiber cable. In this paper, we will consider the parallel array (PA), the discontinuous series (DS) system and the intrinsic-reference ladder (IRL) system, and compare them with regard to noise performance and practical implementation aspects. A modification to the IRL-system is proposed, resulting in a significant improvement in the theoretical noise performance.

1 Coherence multiplexing (CM)

Coherence multiplexing (CM) is a simple form of optical code division multiplexing, in which broadband sources and delay-lines are used to multiplex signals from distinct users over one optical fiber cable [1]-[7]. A simple CM-configuration is shown in Figure 1, which depicts one transmitter and one receiver. The transmitter consists of a broadband light source (for example an LED) and a Mach-Zehnder interferometer (MZI) having a path-imbalance T_{Tx} which is much larger than the coherence time τ_c of the source. Moreover, one of the paths contains an in-line modulator which imposes a phase modulation $\phi_{mod}(t)$ on the lightwave taking the lower path of the MZI. Therefore, the two lightwaves that are launched into the transmission fiber are mutually incoherent, such that the phase modulation $\phi_{mod}(t)$ does not result in a visible intensity modulation in the transmitted signal. The receiver consists of an MZI, having path-imbalance $T_{Rx} \gg \tau_c$, and a balanced photodiode pair. It can be proven that the combination of the rightmost 2×2-coupler and the photodiodes acts as a balanced mixer [5]. Hence, when the difference between T_{Tx} and T_{Rx} is much larger than τ_c, the output signal $I_{out}(t)$ of the receiver only contains zero-mean optical beat interference (OBI) noise, as all lightwaves mix incoherently in that case. When that difference is much smaller than τ_c, however, the lightwave taking the upper path in the transmitter and the lower path in the receiver mixes coherently with the lightwave taking the lower path in the transmitter and the upper path in the receiver. The resulting output signal has an expected value which is then given by $E[I_{out}(t)] = A\sin(\Delta\phi(t))$, where A is proportional to the received power and the responsivities of the photodiodes. $\Delta\phi(t)$ is the phase difference between the coherently mixed lightwaves, which is given by $\Delta\phi(t) = 2\pi f_c (T_{Rx} - T_{Tx}) + \phi_{mod}(t) + \frac{\pi}{2}$, where f_c
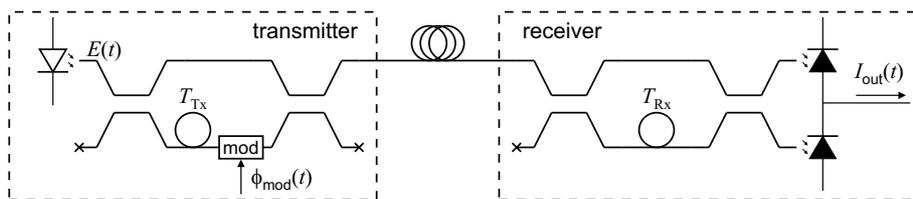

Figure 1: Coherence multiplex system with one transmitter and one receiver

is the carrier frequency of the light. Hence, digital transmission can be accomplished by performing binary phase shift keying (PSK) modulation in the transmitter ($\phi_{\mathrm{mod}} = 0$ for a binary one and $\phi_{\mathrm{mod}} = \pi$ for a binary zero), and by carefully controlling the relation between T_{Tx} and T_{Rx}, for example by means of a feedback loop from the output signal to T_{Rx}. In that case, the expected output signal is $A\cos(\phi_{\mathrm{mod}}(t))$, which is a baseband polar NRZ signal taking values $+A$ and $-A$ that correspond to the transmitted information. Using multiple transmitters, several channels can be multiplexed onto an optical fiber cable, provided that the values of the delays in the transmitters are mutually separated by a value that is much larger than τ_{c}. The performance of the system is mainly limited by OBI noise [3, 4, 5], which is caused by the incoherent mixing of lightwaves from both the desired user and the interfering users. The power spectral density of this noise decreases with increasing source bandwidth and increases with increasing number of users. Multiplexing can be performed in several ways. Brooks et al. [1] introduced four architectures in which a common source is shared for multiplexing interferometric sensor signals: the discontinuous series (DS) system, the continuous series (CS) system, the extrinsic-reference ladder (ERL) system, and the the intrinsic-reference ladder (IRL) system. The CS and ERL system require two transmission fibers to connect the transmitters to the receivers. This is not very practical for communication systems, because the polarization states of the lightwaves at the outputs of the two fibers need to be matched in order to achieve optimal interference. Therefore, these will not be considered in this paper. Another configuration that will be considered in this paper is the parallel array (PA), which was introduced by Goedgebuer and Hamel [2]. Unlike the performance analyses by Wentworth [3] and Chu and Dickey [4], the comparison of these three architectures will be based on a balanced receiver (see Figure 1) rather than a single-ended receiver, as a balanced receiver has proven to result in a superior performance [5]. Moreover, some attention will be paid to practical implementation aspects.

2   The parallel array (PA)

The most straightforward CM topology is the parallel array (PA), which consists of several (say N) distinct MZIs, each illuminated by it own source; see Fig. 2. Each MZI has a different path imbalance $T_{\mathrm{Tx},i}$ and modulating signal $\phi_{\mathrm{mod},i}(t)$. The output signals of the MZIs are combined using an $N \times 1$-coupler and launched into the common fiber. The path imbalances $T_{\mathrm{Tx},i}$ have to be spaced apart much more than

Figure 2: The parallel array (PA)

the coherence time τ_{c} in order to avoid crosstalk between the users. When thermal light is assumed [3], the signal-to-OBI noise ratio after filtering with electrical bandwidth B in the receiver is given by [5]

$$SNR_{\mathrm{OBI,par}} = \frac{1}{(4N^2 + 2N + 1)\, B\, \tau_{\mathrm{c}}} \qquad (1)$$

where B is chosen such that the filter does not affect the desired signal. The particular advantage of the parallel array configuration is that it provides maximum freedom in locating the users, and that simple OOK modulation can be performed instead of phase modulation, for example by directly modulating the source power.
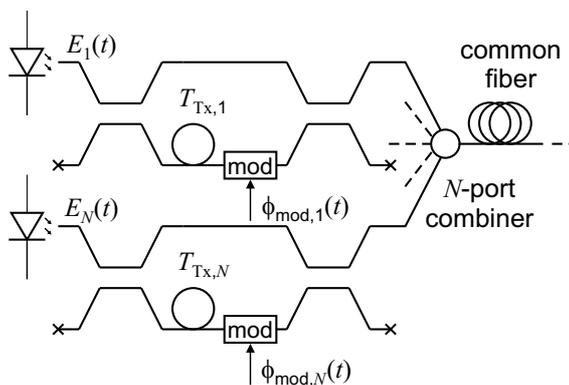
3 The single intrinsic-reference ladder (SIRL) system

In the intrinsic-reference ladder (IRL) system as proposed by Brooks et al. [1], several MZIs are configured in parallel and illuminated by a common source. For reasons that will become apparent later, however, we prefer to describe the system as a two-arm interferometer of which the lower arm is subdivided in N subbranches, each subbranch having its own path delay $T_{\mathrm{Tx},i}$ with respect to the upper arm and phase modulation $\phi_{\mathrm{mod},i}(t)$; see Fig. 3. We term
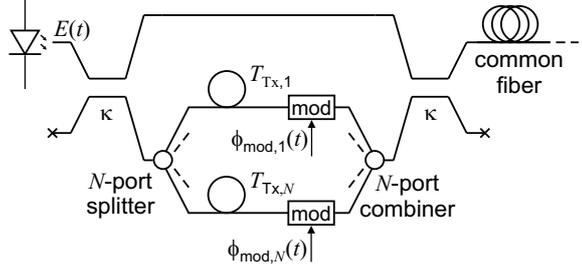

Figure 3: The single intrinsic-reference ladder (SIRL) system

this system the single intrinsic-reference ladder (SIRL) system. Crosstalk between the channels can be avoided for example by setting $T_{\mathrm{Tx},1} \gg \tau_{\mathrm{c}}$ and choosing the other $T_{\mathrm{Tx},i}$s as odd multiples of $T_{\mathrm{Tx},1}$. When the power coupling constants of the (non-uniform) 2×2-couplers are set to κ, the signal-to-OBI noise ratio at the output of the filter can be proven to be given by

$$SNR_{\mathrm{OBI,IRL}} = \frac{N \kappa^2 (1-\kappa)^2}{\left[\kappa^4 N^3 + \kappa^2 (1-\kappa)^2 (4N^2 + N) + (1-\kappa)^4 (2N-1) \right] B \, \tau_{\mathrm{c}}} \tag{2}$$

Using ordinary 3 dB couplers gives $\kappa = \frac{1}{2}$, resulting in

$$SNR_{\mathrm{OBI,IRL}} = \frac{N}{(N^3 + 4N^2 + 3N - 1) B \, \tau_{\mathrm{c}}} \tag{3}$$

Optimizing (2) with respect to κ, however, results in

$$\kappa_{\mathrm{opt}} = \frac{\sqrt[4]{2N^2 - N}}{N + \sqrt[4]{2N^2 - N}}, \ SNR_{\mathrm{OBI,IRL,max}} = \frac{1}{\left(4N + 1 + 2\sqrt{2N^2 - N} \, \right) B \, \tau_{\mathrm{c}}} \tag{4}$$

which, particularly for large N, is superior to (1). A particular disadvantage of the SIRL system, however, is that it requires a more advanced optical integrated circuit than the PA. Moreover, it requires the different users to be localized to a single node, such that the SIRL system is solely useful for transmission in the downlink direction of a distribution network.

4 The discontinuous series (DS) system

In the discontinuous series (DS) system, N MZIs are cascaded in series, each MZI having its own path imbalance $T_{\mathrm{Tx},i}$ and modulating signal $\phi_{\mathrm{mod},i}(t)$; see Fig. 4. The problem of assigning proper values to the $T_{\mathrm{Tx},i}$s is not straightforward; this is extensively discussed in [6], showing that the maximum path imbalance grows very rapidly with increasing N. Another disadvantage of the DS system, which -to our knowledge- has not been reported so far, is that in the receiver, coherent interference occurs in several mutually time-shifted pairs of lightwaves, resulting in a distorted output signal. This effect increases with increasing N and path delays, and is particularly troublesome in systems for high-frequency signal transport, for example Radio over Fiber transmission [7]. As long as this effect is negligible, however, the signal-to-OBI noise ratio after filtering can be shown to be

$$SNR_{\mathrm{OBI,DS}} = \frac{1}{\left[4 \left(\frac{3}{2} \right)^N + 1 \right] B \, \tau_{\mathrm{c}}} \tag{5}$$
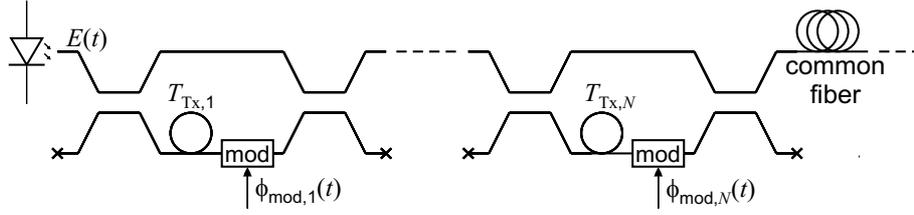
Figure 4: The discontinuous series (DS) system

In Figure 5, the SNRs of the discussed systems are plotted as function of the number of users N, normalized to the SNR for $N = 1$ (note that the latter is the same for all topologies). Obviously, the DS system performs the best for a small number of channels ($N < 6$), and for larger values, the performance rapidly degrades with increasing N.

Although the users in the DS system do not need to be localized to a single node, they are restricted to be configured in a bus topology, which is less flexible than a parallel array, but more flexible than a SIRL system. The complexity of the optical circuits is comparable to the parallel array, but the advantage is that only one source (rather than N sources) is required.
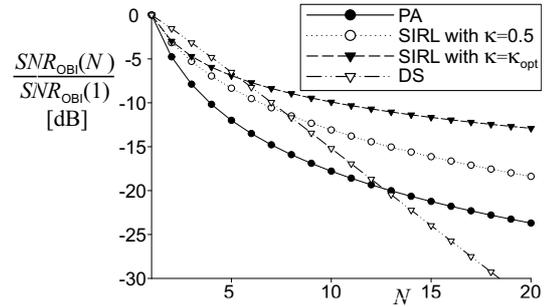

Figure 5: Normalized SNRs

5 Conclusion

Three topologies for performing coherence multiplexing were considered. Each topology turned out to have its advantages and disadvantages. Choice for a particular topology depends on several criteria like number of users, location of the users, bandwidth of the signals to be transported and allowed system complexity. For large number of users, the SIRL system shows a superior OBI noise performance, which -to our knowledge- has not been reported so far.

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