# Direct Digital Modulated Message Channel for Passive Metro WDM Systems

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## Kurzfassung

In Niedrigpreis-WDM-PON Lösungen werden abstimmbare Transceiver auf der Remote-Seite verwendet, deren Wellenlängenregelung ferngesteuert über einen Kommunikationskanal erfolgt. In diesem Beitrag wird ein Modulationsverfahren beschrieben, welches mit geringstem Hardwareaufwand eine für diese Anwendung ausreichend hohe Leistungsfähigkeit dieses Kanals realisiert. Dies soll die Integration der ferngesteuerten Wellenlängenregelung in kleine Transceiver-Gehäuse, wie z.B. ein Standard-SFP+ Gehäuse, ermöglichen.

## Abstract

Low-cost WDM-PON solutions include tuneable lasers at the tail-end site. The laser tuning is remotely controlled by a message channel (MC). We report on a modulation principle that ensures a sufficient performance for that purpose at smallest hardware effort. This is the precondition for the integration of the respective hardware into small transceiver packages, i.e. a standard SFP+ package.

## 1 Introduction

A strong increase of mobile bandwidth has been observed during the recent years. New technologies are needed to support this trend. For next-generation radio access networks and broadband backhaul, wavelength division multiplexing passive optical networks (WDM-PON) are considered. Low cost tunable lasers at the remote sites together with a centralized wavelength locker are proposed for saving cost and effort. Channel tagging and remote wavelength control is supported by a transparently added downstream signaling channel and upstream per-channel pilot tones [1 - 4]. This downstream signaling channel is called Head to Tail Message Channel (HTMC) in the current draft of ITU-T SG15 G.metro, where this type of system is currently being standardized.
To connect the head end, or OLT, with each tail end, or ONU, the power envelope of each WDM data channel is modulated with a low modulation depth. Therefore, the OLT communicates with each ONU via a separated message channel **(Figure 1)**.

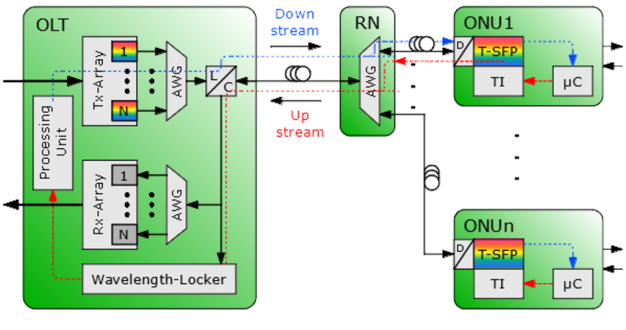


**Figure 1:** WDM-PON system with remotely controlled lasers

## 2 Requirements

The reliability and practicability of remote wavelength controlled WDM-PON - has been demonstrated in several field trials [5 - 7]. The use of that principle results in a significant reduction of the cost in an operational network. After the successful and error free demonstration of the prototype, the next step is turning G.metro technology into practical use.
For practical implementation, the complete hardware has to be integrated in a standard transceiver, i.e. an SFP (small form factor pluggable). While tunable transceivers have been available as SFP+ form factor, additional effort is required to integrate the message channel between OLT and ONU, while maintaining the form factor.

### 2.1 Performance

The required performance of the message channel is dictated by the application of laser tuning with centralized wavelength locking. To limit the control cycle time, a data rate of at least 50 kbps is required. This limits the time required for a 48-bit message to approximately 1 ms, corresponding to the round-trip time over 100 km of fiber. To avoid an abundance of dropped messages, a bit error rate (BER) of better than $5 \cdot 10^{-6}$ should be achieved. On the other hand, the modulation depth of the message channel needs to be low enough to keep the impact of the message channel on the optical payload data below 0.5 dB. Furthermore, an optical power dynamic range of more than 3 decades is required to enable operation even for a low quality downstream channel.

## 2.2 Power and space constraints

High performance hardware for the message channel need to fit in the limited space in the transceiver. Discrete ADCs and DACs can therefore not be used, only the ADC/DACs included in the module controller are available. A current mirror for decoupling the channel signal from the payload is required as well as an amplifier covering the required dynamic range, which can be achieved using a logarithmic amplifier, which also needs to adapt the signal level to the microcontroller input.

## 2.3 Microcontroller

To keep the amount of additional hardware low, we assume that there is only a low cost microcontroller available. It has to manage the transceiver tasks and has to execute the processes regarding the message channel. After detection of the optical signal, the low-frequency management channel is separated from the broadband payload channel and then demodulated or decoded. Clock recovery as well as word and frame synchronization are required.

# 3 Implementation

## 3.1 Modulation format

To avoid the requirement for additional analog hardware and the ability to use digital I/O ports of the existing microcontroller, a direct digital modulation format was chosen.
This choice leads to some further advantages. A direct digital modulation principle enables a simple clock and data recovery using a software based phase locked loop (PLL). An adaption of the data eye sample point is also possible with little effort. Microcontroller internals like counter and capture compare registers (available inside all low cost microcontrollers) simplify the data packet synchronization.

## 3.2 Coding: Manchester code

Direct digital modulation principles do not need an RF carrier. The requirements to the transmission medium regarding DC bias and clock recovering are met by the Manchester coding scheme. The Manchester coding is a pulse position modulation format or also known as phase encoding (PE). A characteristic feature is that the signal is bias-free and has a low low-frequency content. This is helpful to avoid channel cross talk in case optical amplification is used in the system. Another feature of Manchester coded signals is the self-clocking property, which enables a simple clock recovery algorithms.
Manchester encoded data are derived from the phase of a square wave source clock. So the Manchester code is a special case of binary phase shift keying (BPSK) with a clock as RF-carrier. Therefore it is easier to generate than an analog carrier. Because of the digital character of the carrier a demodulation is not necessary and the data can be directly decoded.

### 3.2.1 Direct encoding

For the representation of coded data according to Manchester code standard there are two different conventions:
A first version was published by Gordon Eric Thomas in 1949, in which a 0 bit is encoded as a low-to-high signal level transition with a low level in the first half of the bit period and a high level in the second half, while a 1 bit is encoded with the inverted phase.
The second convention is specified in IEEE 802.3 (Ethernet) and IEEE 802.4 (Token bus) standards. It is the inverted version of a G.E. Thomas signal.

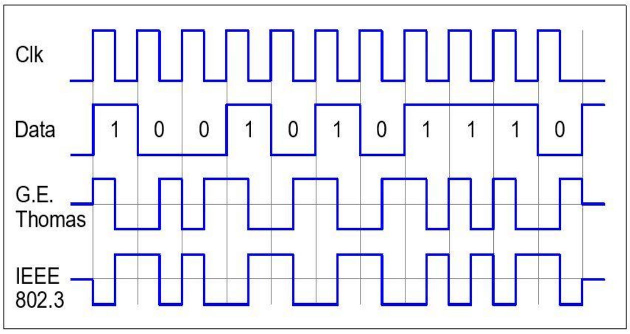


**Figure 2:** Manchester coding conventions

The two conventions of direct phase encoding of the Manchester code are shown in **Figure 2**. For a proper decoding of an encoded signal it is necessary to know the polarity. So a synchronization header might be required in the data frame if the polarity is not known.

### 3.2.2 Differential encoding

For polarity agnostic operation, the data pattern is encoded in the phase-change of the clock signal. This differential coding scheme does not require a synchronization header in the frame.

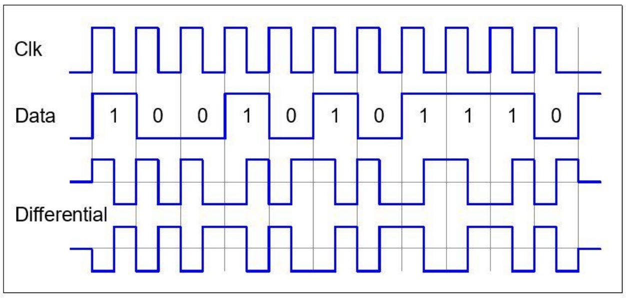


**Figure 3:** Differential Manchester encoding

For a 0 bit in the data stream, the phase of the transmitted 0/1 sequence does not change, while for a 1 bit, the phase is shifted by 180 degrees. As shown in **Figure 3**, in both cases of polarity the phase changes occur at the same time.

## 3.3 Error detection and correction

To avoid wrong tuning of the remote ONU lasers, errors in the MC have to be at least detected or, better, corrected.

In case the error is only detected, the message has to be discharged. For error detection and correction purpose, we chose a (64, 57) extended Hamming code [8], which can be implemented in the microcontroller software. Using seven parity bits for 57 data bits results in a Hamming distance of 4, enabling the correction of one bit error per frame and the detection of frames with two bit errors. Some frames with three bit errors can also be detected. The mean time between discarded or erroneous 64-bit messages in a message channel of 100 kbps is shown in Table 1.

| MC - BER | Mean time between dropped messages | Mean time between erred messages |
|---|---|---|
| $1 \cdot 10^{-6}$ | 3.6 days | 893 years |
| $2 \cdot 10^{-6}$ | 22 h | 125 years |
| $5 \cdot 10^{-6}$ | 3.5 h | 7.8 years |
| $1 \cdot 10^{-5}$ | 53 min | 1 year |
| $2 \cdot 10^{-5}$ | 13 min | 44 days |
| $5 \cdot 10^{-5}$ | 2 min | 3 days |
| $1 \cdot 10^{-4}$ | 32 sec | 8.6 h |

**Table 1:** Mean time for dropped and erred messages as a function of the 100-kpbs message channel bit error rate [4]. The mean time between dropped messages is based on the probability of two-bit errors in a message plus half the probability of three-bit errors in a message, while the mean time between erred messages is based on half the probability of three-bit errors in a message plus probability of four or more bit errors in a message.

While dropped messages only cause delay in the tuning process, erred messages can lead to mistuning and should be avoided. A BER of $5 \cdot 10^{-6}$ at 100 kbps leads to some triple errors in a message or more every ~8 years. They cannot be detected and lead to erred messages [4].

# 4 Experimental setup

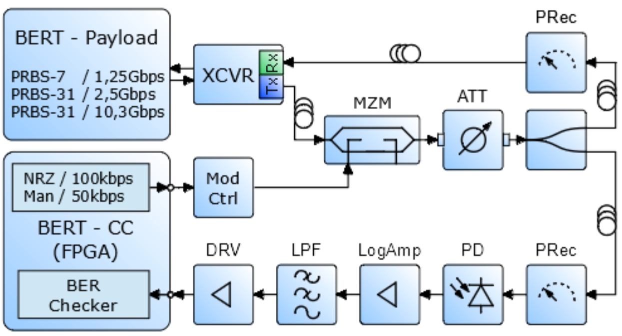


**Figure 4:** Setup to evaluate interference between payload and message channel

The test setup to evaluate the performance of the direct digital modulation is shown in **Figure 4**. An MC signal generated by a field programmable gate array (FPGA) is modulated onto an optical payload signal using a Mach-Zehnder-Modulator (MZM). For the receiver, minimum footprint high performance components are chosen. The logarithmic amplifier enables a dynamic range over 5 decades. For suppression of high frequencies, a low pass filter 5th order with a cutoff frequency of 78.6 kHz is used. A BER checker for the message channel is implemented in an FPGA. The bit error rate of the high speed (payload) signal is measured by a Bit Error Rate Tester (BERT) after the high speed receiver.
Measurements were done at payload data rates of 1.25 Gbps up to 10 Gbps and MC data rates of 10 kbps to 1000 kbps in combination with modulation depths from 2% to 10%. The modulation depth is defined as $m = 1 - P(0) / P(1)$, where $P(0)$ and $P(1)$ are the average power levels in the mark and space rails of the message channel, respectively.
The MC carried a PRBS-7 pattern and was either NRZ modulated at 100 kpbs or Manchester coded with a data rate of 50 kbps. The main results are shown in **Figures 5, 6, and 7**.

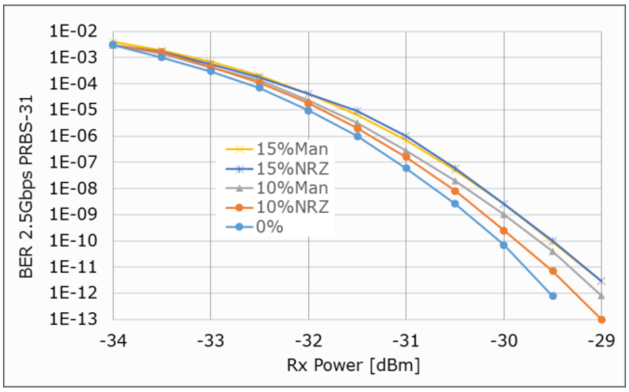


**Figure 5:** Impact of message channel onto 2.5 Gbps payload channel for 10% and 15% modulation depth with NRZ and Manchester coding

In **Figure 5**, the BER of the 2.5-Gbps PRBS-31 payload channel is depicted vs. the optical receiver input power. The payload channel was additionally modulated by a message channel carrying a PRBS-7 pattern with different modulation depths and modulation schemes. Very similar results are obtained for a 100-kbps NRZ signal and a 50-kbps Manchester coded signal for modulation depths of 0%, 10% and 15%. The payload power penalty caused by the Manchester coded MC with a modulation depth of 10% is approximately 0.5 dB compared to the signal without MC (0%) at a BER of $10^{-12}$. The results for the 15% Manchester coded signal nearly coincide with the 15% NRZ signal.
A data rate of 2.5 Gbps with a PRBS-31 bit sequence represents the worst case payload, as it has the lowest frequency components to interfere with the MC.
Data rates of 1.25 Gbps (GbE) are typically 8B/10B encoded, and 10 Gbps have a higher clock frequency, both resulting in less impact by the low-frequency MC modulation see **Figure 6**.

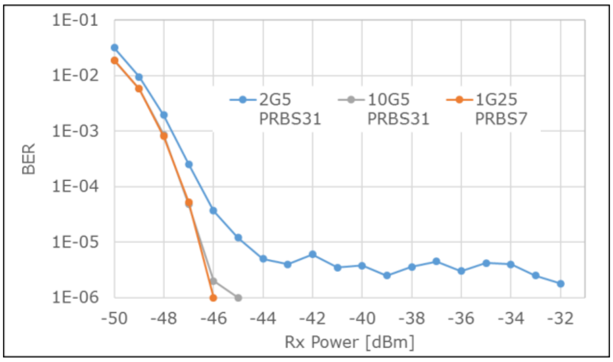


**Figure 6:** BER of message channel for different payload data rates at 10% modulation depth of 100 kbps NRZ coded message channel

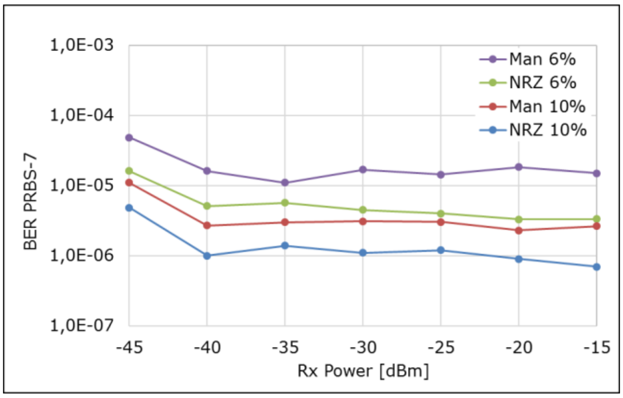


**Figure 7:** BER of message channel as function of received optical power modulated onto a 2.5 Gbps payload channel. NRZ modulation: 100 kpbs, Manchester modulation: 50 kbps

**Figure 7** shows the BER of the MC as a function of the received power. The influence of the payload channel (2.5 Gbps, PRBS-31) can be seen, as an error floor is observed even for high received power, caused by the spectral components of the payload signal that fall into the frequency range of the MC. The error floor is lower for a higher modulation depth. As in the measurements shown above, the MC NRZ-signal works at 100 kbps, the Manchester coded version works at 50 kpbs. Due to the different spectral distributions, the NRZ signal achieves a better performance than the Manchester coded signal. For a Manchester coded MC at 50 kbps and 10% modulation depth a bit error rate of lower than $3{\cdot}10^{-6}$ is already achieved at an optical power of -40dBm.

The Manchester decoders for standard as well as for differential Manchester coded signals work with a signal edge based synchronization. So the BER Measurements at differential Manchester coded signals compared to standard Manchester coded signals return the same results. The influence to the payload is the same for standard and differential Manchester coded signals in that setup.

# 5 Conclusions

For low cost WDM-PON solutions the functionalities for laser tuning and communication need to be inside an SFP+ package in addition to the standard functions. A main feature is a message channel to connect the OLT to each ONU by envelope modulation of the payload channel. Direct digital modulation, using lowest additional effort, has been demonstrated for a data rate of 50 kbps at a bit error rate of lower than $5{\cdot}10^{-6}$ at 10% modulation depth. So the direct digital modulation format presented in this paper is suitable for the requirements in low cost WDM-PON.

# 6 Future Activities

In the ITU-T (International Telecommunication Union-Telecommunication Standardization Sector) SG15 (Study Group 15), a new standard is under development under the working title G.metro. Centralized wavelength tuning based on a Manchester coded Head to Tail Message Channel (HTMC) in combination with upstream per-channel pilot tones has been included in the current draft. Further input will be required to specify details of the transmission system.

# 7 Acknowledgement

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