A SIMPLE SYSTEM UPGRADE FROM BINARY TO DUOBINARY

W. Kaiser, T. Wuth, M. Wichers and W. Rosenkranz

University of Kiel, Chair for Communications, Kaiserstr. 2, 24143 Kiel, Germany,
Phone: +49 431 880 6305, Fax: +49 431 880 6303, email: wk@tf.uni-kiel.de

Introduction

The feasibility of high capacity optical transmission systems in the Tb/s-range has been demonstrated using bit rates of 10 Gb/s or 40 Gb/s in combination with dense WDM system configurations. A key technology to further extend this capacity is bandwidth efficient modulation formats, such as duobinary, single sideband (SSB) or multilevel modulation [1,2]. However, multilevel modulation is handicapped by using a complex receiver design whereas single sideband modulation is (up to now) limited by a poor extinction ratio due to the required linearity of the used modulator.

Optical duobinary coding, in contrast, is an effective method for high-speed optical transmission systems to improve the spectral efficiency and to increase the dispersion tolerance. These essential benefits have been reported for 10 Gb/s- and 40 Gb/s-systems in [3-5] and [6], respectively.

When utilizing duobinary coding in practical systems, two main issues have to be considered: duobinary precoding and overall transmitter setup complexity.

In this contribution we present both a simple (alternative) duobinary precoder using standard logic ICs and a transmitter configuration with a standard single-arm Mach-Zehnder modulator (MZM) resulting in a reduced complexity setup and in negligible symmetry requirements. With this setup we are able to demonstrate data transmission at 10 Gb/s over a record length of 252 km of uncompensated standard single mode fiber (SSMF). Upgrading this setup to 40 Gb/s is straightforward and will reveal the enormous benefits of duobinary coding in upcoming optical transmission systems.

Duobinary transmission overview: basics and benefits

Duobinary coding was invented in the 1960s by A. Lender [7,8] and has been adapted to or "re-invented to" optical transmission in the mid 1990s [9,10]. As an advanced modulation format, it has been intensively studied since. Some of the well-known basics and the resulting benefits are summarized, focusing on practical aspects for a system upgrade from binary to duobinary.

Figure 1 shows both the schematic and the possible hardware implementation of duobinary coding and decoding with corresponding functional blocks.

The binary input data $d(k)$ is precoded (to $b(k)$, still a two level signal) and then duobinary encoded with a delay-and-add operation, resulting in a three level signal $c(k)$ with symbols $\{0, 1, 2\}$. The duobinary encoding can be implemented either with a combination of a delay-and-add operation (using RF power-splitters and delay lines) followed by a band limiting lowpass filter or with a single analog lowpass filter (duobinary filter). The required offset is a simple AC-coupling. To convert the symbols $c_{AC}(k) = \{-1, 0, +1\}$ into optical signals a Mach-Zehnder modulator (MZM) is used capable of modulating both amplitude and phase. Note, that in the duobinary case the electrical field is modulated rather than the optical power or optical intensity. The symbols "-1" and "+1" have identical intensities but show a phase difference of π. The different ways of operating the MZM for both binary and duobinary modulation is illustrated in Figure 2. The decoding at the receiver is done by the photodiode via the magnitude squared operation ($|...|^2$), automatically. Therefore a standard (binary) receiver can be used.

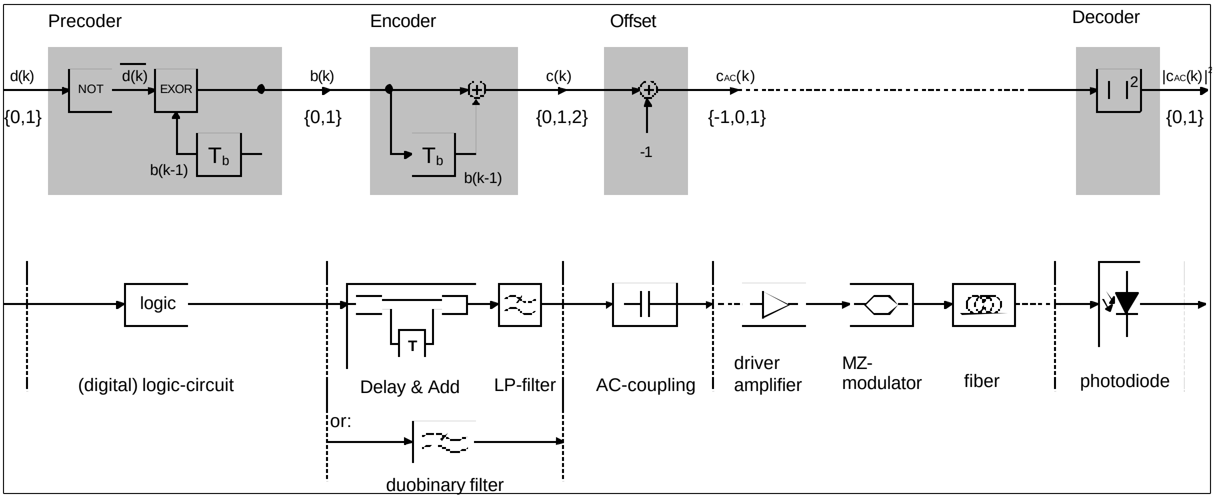

Figure 1: Overview of duobinary transmission: schematic (top) with precoder, encoder, offset and decoder and possible hardware implementation (bottom) for corresponding functional blocks.

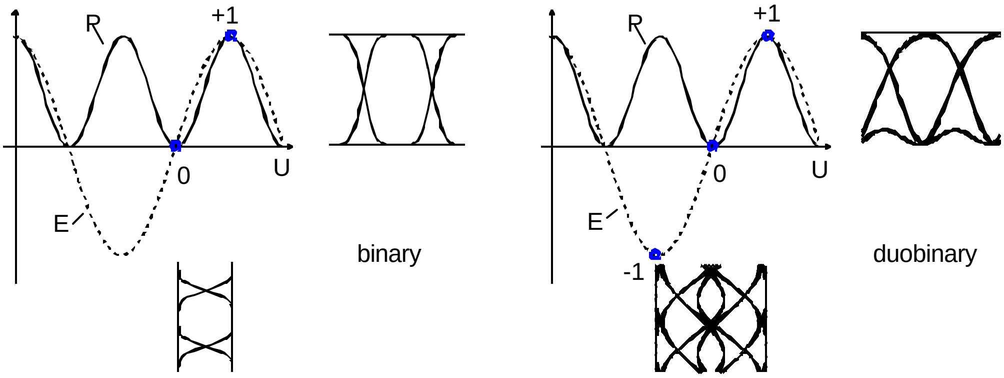

Figure 2: MZM transfer characteristic of both electrical field (E) and optical power (P) for (conventional) binary modulation (left) and duobinary modulation (right).

The precoder at the transmitter is required in order to allow easy data recovery at the receiver. Without a precoder the binary data signal can be recovered (using the inverse functionality of the encoder) but the current data depends on the current bit and on the previous bit. Such a recursive receiver is sensitive to error propagation and is therefore not practical.

In Table 1 the functional correspondence of the data sequences are summarized.

For further illustration a sample bit sequence (001101001) is considered and the modified bit sequence after each functional coding block is displayed in Table 2. After optical transmission the original input bit sequence can be recovered at the receiver.

Table 1: Summary of duobinary coding and decoding rules

duobinary precoding	$b(k) = \overline{d(k)} \oplus b(k-1)$
duobinary encoding	$c(k) = b(k) + b(k-1)$
offset	$c_{AC}(k) = c(k) - 1$
duobinary decoding	$\hat{d}(k) = \lvert c_{AC}(k) \rvert$

Table 2: Illustration of duobinary coding and decoding process with a sample bit sequence

input data	$d(k)$	1	0	0	1	1	0	1	0	0	1
	$\overline{d(k)}$		1	1	0	0	1	0	1	1	0
duobinary precoding	$b(k)$	1	0	1	1	1	0	0	1	0	0
duobinary encoding	$c(k)$		1	1	2	2	1	0	1	1	0
offset	$c_{AC}(k)$		0	0	1	1	0	-1	0	0	-1
		--- optical transmission ---									
duobinary decoding	$\lvert c_{AC}(k) \rvert$		0	0	1	1	0	1	0	0	1

The spectral shaping due to duobinary encoding results in a bandwidth reduction of about one half compared to conventional binary modulation. The measured power density spectra before and after duobinary coding are shown in Figure 3. Note, that the used duobinary filter (lowpass) has a 3 dB cutoff frequency of a quarter of the bit frequency.

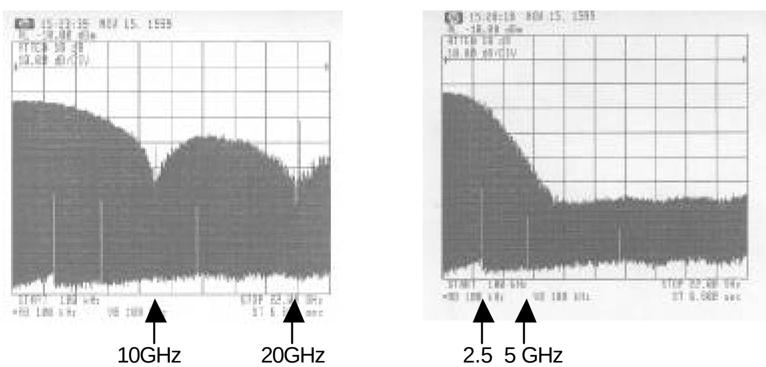

Figure 3: Measured power density spectra of 10Gb/s data before (left) and after (right) duobinary coding showing the bandwidth reduction.

This bandwidth reduction results in an increased dispersion tolerance of duobinary transmission compared to conventional binary transmission. This well known benefit is illustrated in Figure 4. The eye opening penalty (EOP) normalized to the back-to-back eye opening of binary transmission is plotted versus the residual dispersion in Figure 4 (left). In Figure 4 (right) the dispersion tolerance is calculated for various fiber input power. In summary, duobinary transmission offers more than twice the amount of dispersion tolerance in the linear regime that can be used for both dispersion uncompensated or dispersion-managed fiber links. This advantage is substantially reduced for optical input powers >8dBm. In the nonlinear regime, both modulation formats show comparable performance in terms of dispersion tolerance and compensation scheme (optimum residual dispersion).

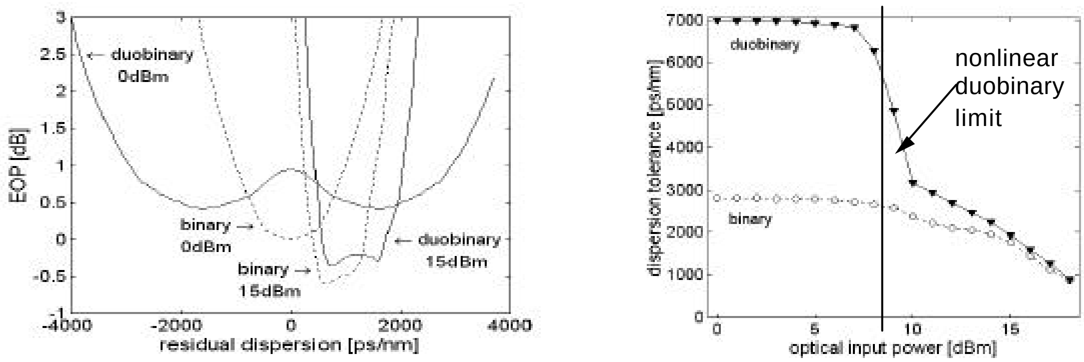

Figure 4: Comparison of transmission characteristics for binary and duobinary modulation at 10 Gb/s (simulation results): EOP versus residual dispersion for linear (0 dBm) and nonlinear (+15 dBm) transmission (left) and dispersion tolerance (Q>10) related to optical input power after 100km SSMF (right).

For utilizing these advantages and benefits of duobinary coding in practical systems two main issues have to be considered: duobinary precoding and overall transmitter setup complexity.

Duobinary precoder

Inherent for duobinary coding as a form of partial response signaling is the need for a precoder in order to avoid error propagation and additional hardware complexity at the receiver. With such a precoder, a conventional (binary) optical receiver can be used. Up to now, almost all optical duobinary transmission experiments were performed without a precoder. Due to the properties of the commonly used pseudo random bit sequences (PRBS) the precoder output bit stream is identical to its time delayed input bit stream [11]. Therefore, the functionality of the precoder can be omitted for laboratory use; however, transmitting actual data traffic with duobinary coding without a precoder is not possible.

An implementation of a duobinary precoder in a straightforward way uses a logic EXOR-gate with an external feedback tap with one bit delay; see Figure 5. Both the feedback itself using microstrip lines and the exact adjustment of the delay time (T_b) are critical and hard to implement at high data rates of 10 Gb/s and more. Only one hardware realization effort in this manner is reported so far [12] but with limited operation capabilities due to this external feedback tap. In [13] a 1-chip precoder IC operating at 10 Gb/s was used implementing the EXOR gate with an internal "on-chip" feedback. However, upgrading this precoder structure to higher bit rates seems still be very difficult since in [14] a precoder IC module is reported overcoming this speed limit by parallel processing of the precoding before electrical multiplexing with data rates of one half or one quarter of the transmission bit rate.

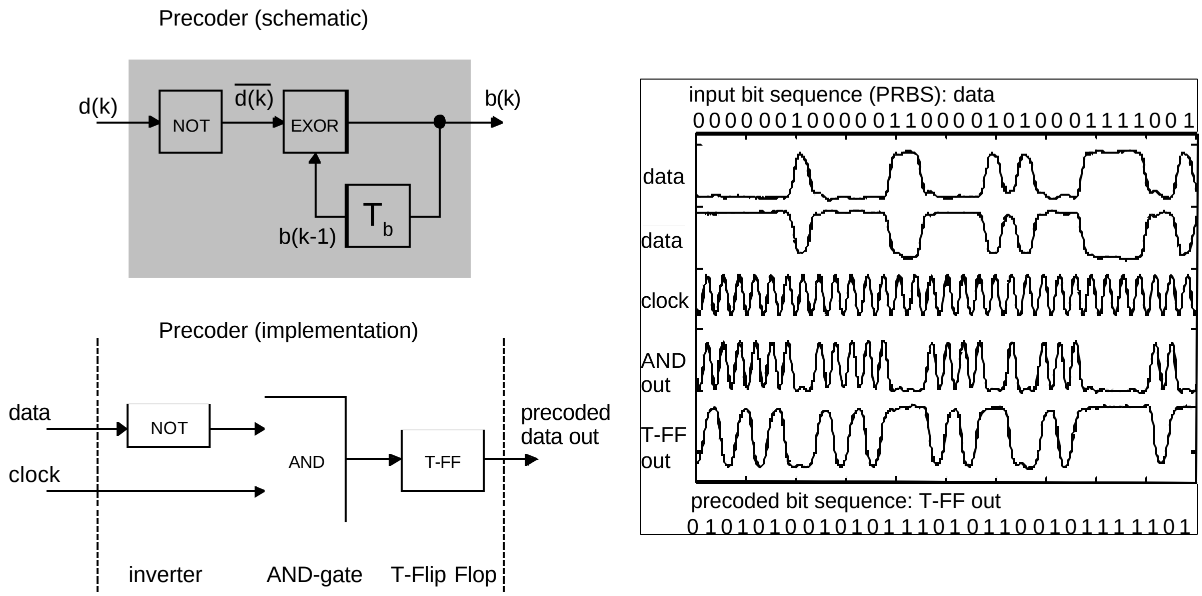

Figure 5: Schematic of duobinary precoder (left top) and our proposed simple realisation (left bottom) with inverter, AND-gate and T-Flip Flop using standard logic ICs without external feedback. The measured bit sequences at 10 Gb/s (right) after each coding block are shown illustrating the functionality of the proposed precoder.

Our proposal of a simple and alternative realization of the precoder is shown in Figure 5 (left). The functionality of the precoder can be established connecting an inverter and an AND-gate followed by a toggle flip flop (T-FF), and therefore using standard logic ICs. No external feedback is required since the recursion is an integral function of the T-FF. Consequently, this precoder structure using only feedforward building blocks avoids all problems with implementation and adjustment. Besides, an upgrade to higher bit rates or a single-chip integration is straightforward.

In our hardware setup we used commercially available standard 10 Gb/s logic ICs. Figure 5 (right) shows measured bit sequences at 10 Gb/s and illustrates the operation of the precoder. The corresponding input and output (logic) bit sequences are also depicted in Figure 5. The experimental verification of our proposed simple precoder was carried out with a transmission experiment with precoding, encoding (duobinary filter) and optical transmission in back-to-back configuration (0 km) and over 150 km standard single mode fiber (SSMF). A standard (binary) preamplified receiver was used. We performed BER-measurements with our precoder at various PRBS sequence lengths (2^7-1 to 2^{31}-1). Error free operation can be stated (BER < 10^{-12}). For a sequence length of 2^{31}-1, we measured a BER of about $1*10^{-10}$. This is due to reduced low-frequency response of the receiver used in our setup. Therefore, it can be noted that there is no drawback for duobinary transmission with long bit sequences, which is a commonly spread restriction of duobinary transmission [15].

Duobinary transmitter setup complexity

In addition, common to all reported high-speed transmission experiments is the use of a duobinary transmitter with a dual-arm Mach-Zehnder modulator (MZM), see Figure 6 (left). However, due to dual-arm configuration this setup requires the parallel implementation of two duobinary encoders and two modulator drivers with significantly increased symmetry requirements on the overall setup and the used components. A detailed numerical analysis addressing these symmetry requirements is reported in [16]. Design guidelines can be extracted resulting in substantially tighter specifications compared to binary

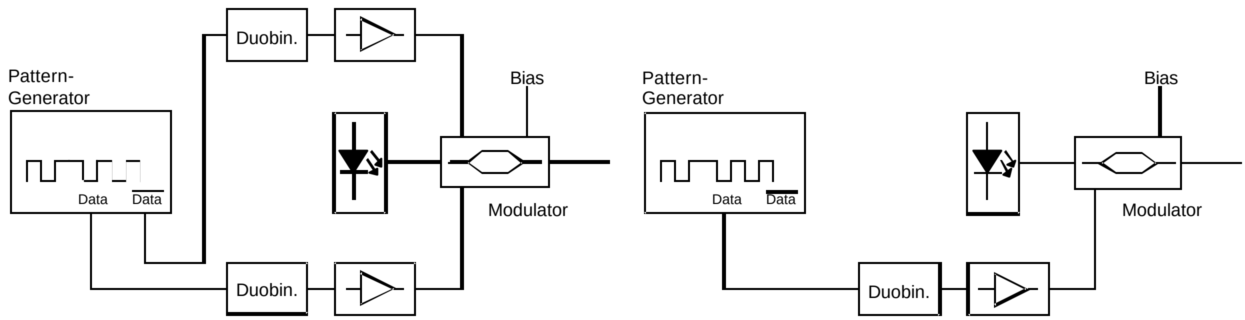

Figure 6: Conventional duobinary transmitter setup with dual-arm MZM (left) and our proposed transmitter configuration with reduced complexity with a standard single-arm MZM (right).

transmitters, concerning mainly delay and bandwidth difference between the two modulator signal arms due to differences in frequency responses of the duobinary filters and the driver amplifiers. In addition, these symmetry requirements are identified as a major drawback for implementing duobinary modulation in 40 Gb/s systems [17].

Our proposed transmitter setup is shown in Figure 6 (right) using a standard single-arm Mach-Zehnder modulator, a single duobinary filter and a single driver amplifier. Thus, this setup avoids all symmetry requirements. The single-arm MZM with internal push-pull configuration provides the same amplitude and phase modulation capabilities as a dual-arm MZM (in push-pull configuration assuming identical complementary input signals). Internal push-pull operation can be established using an MZM layout with a center electrode and symmetrical ground plates. Using such a single-arm MZM for our duobinary coding application implicates the actual innovation in our setup resulting in dramatically reduced complexity and in an improved transmission performance.

Duobinary transmission experiments

In order to evaluate the performance of our proposed transmitter setup we performed transmission experiments and measured the receiver power versus BER for various fiber lengths. Experimental results are displayed in Figures 7 and 8. Our test setup comprises the proposed duobinary transmitter, an optical inline amplifier (placed after 125km of SSMF) and a standard preamplified optical receiver. The fiber

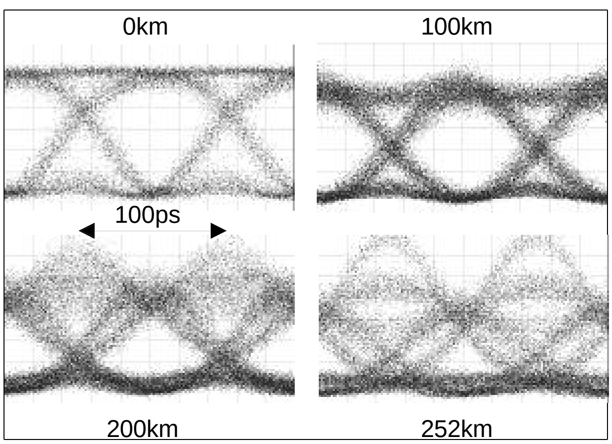

Figure 7. Eye-diagrams of duobinary transmission at 0km, 100km, 200km and 252km of uncompensated SSMF.

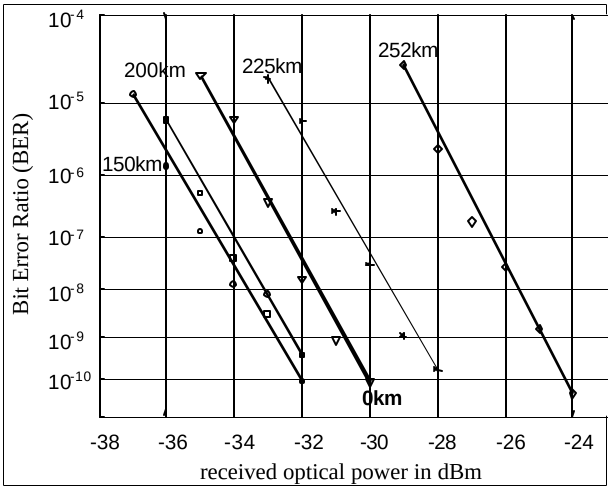

Figure 8: Measured BER versus receiver input power for 0km, 150km, 200km, 225km and 252km transmission distance over uncompensated SSMF.

input power was chosen to 8 dBm (for both fiber spans) according to the results of [4], also displayed in Figure 4 (right). For input powers higher than this 'nonlinear duobinary limit' the dispersion tolerance of this modulation format is starting to decrease substantially. The measured eye diagrams of duobinary transmission are displayed in Figure 7.

A typical duobinary eye shape in back-to-back condition is shown with the use of our simple single-arm MZM setup and only slight degradations after 200 km of uncompensated SSMF can be observed. The eye diagram after 252 km is distorted but error free transmission is still possible. BER measurements at this distance show a receiver sensitivity of about –25 dBm (BER = 10^{-9}) and a penalty compared to back-to-back of about 6 dB, see Figure 8. Note that a negative penalty for transmission distances under 200 km can be observed which is typical for duobinary transmission. For BER measurements a PRBS length of 2^{23}-1 was used.

With our duobinary transmitter setup we are able to bridge 252km of SSMF without any dispersion-compensating device. This is the longest reported distance and it reveals the potential of this modulation format.

Conclusion

Both a simple duobinary precoder implemented with standard logic ICs and a single-arm MZM transmitter configuration with reduced complexity and components requirements are presented. Using our simple precoder and a duobinary filter as an encoder enables the conversion of a standard binary transmission scheme into a duobinary transmission scheme as an add-on or upgrade feature. Since standard logic ICs are used, a precoder upgrade to 40 Gb/s can be done in a straightforward way. With this setup a record length of 252 km of SSMF can be bridged without any dispersion-compensating device.

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