Optical Modulation Formats in PhoSSiL

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PhoSSiL supports a variety of optical modulation formats. These are enumerated and documented in `enum typePulse` in the file `ModulationFormats.hh`. In this document we reproduce that material in a way that is hopefully easier to assimilate.

The formats are in three groups:

(I) Formats that are given by simple analytical mathematical formulae but that are not necessarily experimentally realistic. Typically these provide acceptable pulse shapes in the time domain. However, they tend not to be very accurate in the frequency domain. These formats (numbered with the values used to set them in Signal.in) are

- (1) NRZ
- (2) RZ_GAUSS
- (3) RZ_SECH
- (4) CRZ_GAUSS
- (5) CRZ_RCOS
- (6) CRZ_SIN_MZ
- (11) QPSK_CW
- (12) QPSK_RZ_GAUSS

(II) Formats that are constructed using a phase or Mach-Zehnder modulator. These formats are experimentally realistic but do not always have simple mathematical formulae. They are much more accurate representations of experimentally generated formats than those in Group I, especially in the frequency domain. These formats are

- (14) NRZ_RCOS_MZ
- (15) RZ33_MZ
- (16) RZ50_MZ
- (17) RZ67_MZ

(18) BPSK_PM_NRZ
(19) BPSK_PM_RZ33
(20) BPSK_PM_RZ50
(21) BPSK_PM_RZ67
(22) BPSK_MZ_NRZ
(23) BPSK_MZ_RZ33
(24) BPSK_MZ_RZ50
(25) BPSK_MZ_RZ67
(26) QPSK_SEQ_PM_NRZ
(27) QPSK_SEQ_PM_RZ33
(28) QPSK_SEQ_PM_RZ50
(29) QPSK_SEQ_PM_RZ67
(30) QPSK_DPMZ_NRZ
(31) QPSK_DPMZ_RZ33
(32) QPSK_DPMZ_RZ50
(33) QPSK_DPMZ_RZ67
(34) ODB

(III) Miscellaneous special-purpose formats

(8) CW
(13) INPUT_SIGNAL_FROM_FILE
(9) RZ_GAUSS_PATTERN
(10) INPUT_SEQUENCE
(7) UMBC_RZ

Group II Formats

The electrical signal, $V = V(t)$, is constructed by smoothing a binary signal. The types of smoothing, which are specified using `TypeEOMElecData`, are

(1) EOM_BINARY_DATA_PERFECT_RECT

(2) EOM_BINARY_DATA_ARCTANH_SMOOTHING (Parameter: `EOM_RiseTime`)

(3) EOM_BINARY_DATA_SUPERGAUSS_SMOOTHING (Parameter: `EOM_SuperGaussExponent`)

(4) EOM_BINARY_DATA_RCOS (Parameter: Either optical `RiseTime` or electrical `EOM_RiseTime`. Set the one you don't want to be negative.)

The resulting electrical signal can then be filtered using an electrical filter with `TypeEOMElecFilter` being one of

(0) EOM_NO_ELEC_FILTER

(1) EOM_GAUSSIAN (Parameter: EOM_ElecFilter_FreqFWHM)

(2) EOM_BESSEL (4th-order, with parameter: EOM_ElecFilter_FreqFWHM)

The following two combinations are analyzed in Ho and Kahn, JLT, 22 (2), pp. 658-663, 2004.

- `TypeEOMElecData` = EOM_BINARY_DATA_RCOS
  with `TypeEOMElecFilter` = EOM_NO_ELEC_FILTER
- `TypeEOMElecData` = EOM_BINARY_DATA_PERFECT_RECT
  with `TypeEOMElecFilter` = EOM_BESSEL.

In the case `TypeEOMElecData` = EOM_BINARY_DATA_RCOS, we define

$$V(t) = \sum_k b_k p(t - kT - T/2), \tag{1}$$

where b_k is the binary data (either 0,1 or ± 1) and T = `BitLength`. The pulse shape p is defined in terms of a roll-off parameter, β, that is computed from the rise time input parameter. When $\beta > 0$ the formula for p is

$$p(t) = \begin{cases} 1, & |t| \le \frac{1-\beta}{2}T \\ 0, & |t| \ge \frac{1+\beta}{2}T \\ \frac{1}{2}\left[1 - \sin\left(\frac{\pi(|t| - \frac{T}{2})}{\beta T}\right)\right], & \text{otherwise,} \end{cases} \tag{2}$$

and when $\beta = 0$,

$$p(t) = \begin{cases} 1, & |t| \le \frac{T}{2}, \\ 0, & |t| > \frac{T}{2}. \end{cases} \tag{3}$$

The optical signals, $u = u(t)$, for the modulation formats in Group II are constructed from V as follows.

NRZ_RCOS_MZ

(See Ho and Kahn *op. cit.*) Parameters are

- `TypeEOMElecData` = EOM_BINARY_DATA_RCOS (set automatically in code)
- Either optical `RiseTime` or electrical `EOM_RiseTime`
- `TypeEOMElecFilter` = EOM_NO_ELEC_FILTER (set automatically in code)
- `ExtinctionRatio` in dB
- `ChirpParameter`.

Up to a constant factor, u is given by

$$u_{\mathrm{NRZ}}(t) \;=\; \tfrac{1}{2}\left[\exp\left(\tfrac{i\pi}{4}(1+\alpha)V(t)\right) + i\chi\exp\left(-\tfrac{i\pi}{4}(1-\alpha)V(t)\right)\right], \tag{4}$$

where α = `ChirpParameter` and χ is computed from `ExtinctionRatio`.

RZ33_MZ

(See Ip and Kahn, JLT vol 24, no.3, March 2006, pp. 1610-1618.) Constructed by multiplying NRZ_RCOS_MZ by a train of 33% duty cycle optical pulses. Parameters are as for NRZ_RCOS_MZ. Formula for optical signal is

$$u(t) \;=\; u_{\mathrm{NRZ}}(t)\sin\left[\tfrac{\pi}{2}\left(1+\cos(\pi t/T)\right)\right]. \tag{5}$$

RZ50_MZ

(See Ip and Kahn, JLT vol 24, no.3, March 2006, pp. 1610-1618.) Constructed by multiplying NRZ_RCOS_MZ by a train of 50% duty cycle optical pulses. Parameters are as for NRZ_RCOS_MZ. Formula for optical signal is

$$u(t) \;=\; u_{\mathrm{NRZ}}(t)\sin\left[\tfrac{\pi}{4}\left(1-\cos(2\pi t/T)\right)\right]. \tag{6}$$

RZ67_MZ

(See Ip and Kahn, JLT vol 24, no.3, March 2006, pp. 1610-1618.) Constructed by multiplying NRZ_RCOS_MZ by a train of 67% duty cycle optical pulses. Parameters are as for NRZ_RCOS_MZ. Formula for optical signal is

$$u(t) \;=\; u_{\mathrm{NRZ}}(t)\sin\left[\tfrac{\pi}{2}\sin(\pi t/T)\right]. \tag{7}$$

BPSK_PM_NRZ

Binary phase-shift keyed with constant power. Parameters are

- `TypeEOMElecData` with appropriate parameters (Recommendation: EOM_BINARY_DATA_RCOS)
- `TypeEOMElecFilter` with appropriate parameters (Recommendation: EOM_NO_ELEC_FILTER)

Up to a constant factor, u is given by

$$u(t) \;=\; \exp\left[i\pi(1 - V(t)\right]. \tag{8}$$

So

$$u \;=\; \begin{cases} -1 & \text{if } V = 0, \\ 1 & \text{if } V = 1. \end{cases} \tag{9}$$

Transitions between data symbols lie on the unit circle.

BPSK_MZ_NRZ

Binary phase-shift keying using a Mach Zehnder modulator (MZM). Parameters are

- `TypeEOMElecData` with appropriate parameters (Recommendation: EOM_BINARY_DATA_RCOS)
- `TypeEOMElecFilter` with appropriate parameters (Recommendation: EOM_NO_ELEC_FILTER)
- ε = `MZM_SubOptimalModulationDepthFactor` in range $0 \leq \varepsilon < 0.25$. ($\varepsilon = 0$ is optimal case.)

Up to a constant factor, u is given by

$$u(t) \;=\; \sqrt{P_0}\cos\left\{\pi\left[1 - \varepsilon + (2\varepsilon - 1)V(t)\right]\right\}. \tag{10}$$

So,

$$u \;=\; \begin{cases} \sqrt{P_0}\cos(\pi(1-\varepsilon)) \gtrsim -\sqrt{P_0} & \text{if } V = 0 \\ \sqrt{P_0}\cos(\pi\varepsilon) \lesssim \sqrt{P_0} & \text{if } V = 1. \end{cases} \tag{11}$$

Transitions between data symbols go through the origin.

QPSK_SEQ_PM_NRZ

Sequential binary phase modulation of a CW optical signal using two sequential EOMs. Analogous and spectrally identical to BPSK_PM_NRZ. Parameters are

- `TypeEOMElecData` with appropriate parameters (Recommendation: EOM_BINARY_DATA_RCOS)

- `TypeEOMElecFilter` with appropriate parameters (Recommendation: EOM_NO_ELEC_FILTER)

Up to a constant factor, u is given by

$$u(t) \;=\; \exp\left[i\pi(1-V_1(t)\right]\exp\left[\tfrac{i\pi}{2}(1-V_2(t)\right], \tag{12}$$

where V_1 and V_2 are two electrical signals of the type described above. So,

$$u \;=\; \begin{cases} 1 & \text{if } (V_1,V_2)=(1,1), \\ i & \text{if } (V_1,V_2)=(1,0), \\ -1 & \text{if } (V_1,V_2)=(0,1), \\ -i & \text{if } (V_1,V_2)=(0,0). \end{cases} \tag{13}$$

Transitions between data symbols lie on the unit circle.

QPSK_DPMZ_NRZ

Direct quadrature modulation of a CW optical signal using a dual-parallel MZ EOM. Analogous and spectrally identical to BPSK_MZ_NRZ Parameters are

- `TypeEOMElecData` with appropriate parameters (Recommendation: EOM_BINARY_DATA_RCOS)
- `TypeEOMElecFilter` with appropriate parameters (Recommendation: EOM_NO_ELEC_FILTER)
- ε = `MZM_SubOptimalModulationDepthFactor` in range $0 \le \varepsilon < 0.25$. ($\varepsilon = 0$ is optimal case.)

Up to a constant factor, u is given by

$$u(t) \;=\; \frac{1}{\sqrt{2}}(u_1(t)+iu_2(t)), \tag{14}$$

where

$$u_k(t) \;=\; \sqrt{P_0}\cos\left\{\pi\left[1-\varepsilon+(2\varepsilon-1)V_k(t)\right]\right\}, \tag{15}$$

where V_k for $k=1,2$ are independently generated electrical data streams. So, in case $\varepsilon = 0$,

$$u \;=\; \begin{cases} \frac{1}{\sqrt{2}}(1+i) & \text{if } (V_1,V_2)=(1,1), \\ \frac{1}{\sqrt{2}}(1-i) & \text{if } (V_1,V_2)=(1,0), \\ \frac{1}{\sqrt{2}}(-1+i) & \text{if } (V_1,V_2)=(0,1), \\ \frac{1}{\sqrt{2}}(-1-i) & \text{if } (V_1,V_2)=(0,0). \end{cases} \tag{16}$$

In that case, transitions between data symbols go along the sides and diagonals of a square.

(B/Q)PSK_*_RZ##**

(B/Q)PSK_***_NRZ followed by RZ##_MZ in which u_{NRZ} is replaced by the (B/Q)PSK_***_NRZ optical signal.

Summary for Group II

All formats use electrical data. If we assume this is of `TypeEOMElecData` = EOM_BINARY_DATA_RCOS with `TypeEOMElecFilter` = EOM_NO_ELEC_FILTER then we have parameters as follows for each of the 5 types of NRZ:

- NRZ_RCOS_MZ: EOM_RiseTime (Elec) or RiseTime (Opt); Extinction Ratio (Opt); Chirp (Opt)
- BPSK_PM_NRZ: EOM_RiseTime (Elec)
- QPSK_SEQ_PM_NRZ: EOM_RiseTime (Elec)
- BPSK_MZ_NRZ: EOM_RiseTime (Elec); ε = `MZM_SubOptimalModulationDepthFactor`
- QPSK_DPMZ_NRZ: EOM_RiseTime (Elec); ε = `MZM_SubOptimalModulationDepthFactor`

For each of these 5 formats there are NRZ, RZ33, RZ50 and RZ67 versions. No additional parameters are required for these.