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The Possibility of Applying Spectral Redundancy in Coherent DWDM Systems for Increasing the Data Transmission Rate and Decreasing Nonlinear Effects and Double Rayleigh Scattering with Great Security of Data

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Abstract

A new method coherent DWDM system has been proposed. Standard method uses 90 wavelengths with channel capacity 100 G, so total capacity amounts to 9 Terabit, optical power is P. New "channel super" (CS) consists of 15 wavelengths, number of CS is 6, so total number of wavelengths is 90 too, total capacity is 6 Terabit, but optical power is 4/15P. Over ULH and EULH markets, standard approach will be forced to reduce the total capacity to 2.4 Terabit with optical power 4/15P as in proposed method. But the new can reach 6 Terabit with the same optical power 4/15P.

Keywords

Coherent Communications, Optical Security and Encryption, Fiber Optics Links and Subsystems

1. Introduction

The idea to use spectral redundancy was patented by the Department of Physics, Moscow State University [1]. The development of this method was later suggested [2] with principal improvement—instead of wavelengths, pilots and slaves were proposed. In the present work, a new method of data transmission in coherent DWDM systems is proposed. The existing method, e.g., uses 90 wavelengths 100 G with total capacity 9 Terabit/sec

with average power P. In the new method 6 CS, every with 15 wavelengths is used providing total capacity 6 Terabit/sec with an average power 4/15P. The cross modulation and double Rayleigh scattering are significantly decreased owing to the uniform distribution of power overtime at different wavelengths. The time redundancy (forward error correction (FEC)) is about 20% - 25% and allows one to achieve a net coding enhancement of about 10^{-15} dB by detecting and removing deletions and errors simultaneously. Security of data amounts to 90! $\approx$ 10^{135} combinations. If any laser destroys, BER increases from 10^{-15} to 10^{-12} without interruption.

2. Description of Method

The essence of the method is explained in **Figure 1**. The time is divided into cycles, each of which is equal to 4 microcycles. Eight wavelengths P_{ij} are called pilots (the duration of each wavelength is equal to one cycle) each of which corresponds to a three bit chip: 000 (i = 1), 001 (i = 2), and so on to 111 (i = 8). J = 1 − 4 according 4 QPSK positions. The pilots are shown in **Figure 1** by solid lines. Waves S_{ijk} are called slaves and shown in the figure by dashed lines. Slave S_{1jk} means that, in a given microcycle, the content separated from the current content by one microcycle is transmitted back; S_{2jk} is separated by 2 microcycles, and S_{3jk} is separated by 3 microcycles (j = 1 − 4 according 4 QPSK positions, k is a degenerated factor). Total number of slaves is equal to 7, because there are S_{1j1}, S_{1j2}, S_{2j1}, S_{2j2}, S_{3j1}, S_{3j2} and S_{3j3}. Every slave is sent in sequence, for example as shown on **Figure 1**, where combination S_{3j1}, $S_{3j2,}$ S_{3j3} is necessity. Total number of wavelengths in one "channel super" is equal to 15. Total number of "channel super" is equal to 6. Total number of wavelengths is equal to 90. Before optical MUX with 90 wavelengths optical power of every channel goes through on/off optical switch, which operates with at least micro cycle frequency. Duration of "on" open state is four micro cycles; duration of "off" closed state is zero micro cycle and any more. General scheme is shown on **Figure 2**. Transmitter in every "channel super" works as following both in Ox and Oy polarization (see **Figure 3**).

Every pilot carries 3 bits as colour and 2 bits as QPSK, together 5 bits. In any time there are 4 different wavelengths. During cycle $4 \times 5 = 20$ bits with 15 different wavelengths are transmitted in proposed method against 30 bits with 15 different wavelengths as usually. So total capacity will be 6 times with 15 or 90 different wavelengths, which corresponds to $9 \times (20/30) = 6$ Terabit/sec opposite to 9.0 Terabit/sec in usual method, but power will be 15/4 = 3.75 times less 10 lg 3.75 = 5.74 dB. Over ULH and EULH market nonlinear effects [3] reduce total capacity strongly as shown in **Table 1** [4].

So for reach more than approximately 5000 km provider will turn off a lot of wavelengths (because in nonlinear optics power per channel reduces as P in square when the number of channels is big, opposite as P in linear optics [3] when the number of channels is small), for example in 15/4 times, reducing total power and capacity (see **Table 1** [4]). REAL capacity will be $9 \times 4/15 = 2.4$ Terabit/sec. In new method power will be same but REAL capacity will be again 6 Terabit/sec with DRS 5.74 dB less! Very interesting that there are combinations, when in both approaches transmitter sends absolutely the same, but total capacity differs 2.5 times. Note, that submarine systems cannot be upgraded, so in usual methods double power 2P for two polarizations may be challenge, but our budget is big enough, because $2 \times 4/15P = 8/15P$.

Is such transmitter possible? Answer is easy—yes!

Is corresponding receiver possible? Answer is extremely difficult. We propose next construction shown on **Figure 4** (for simplicity clock or cycle is sent over separate wavelength for all "channel super" in every fiber for cable altogether). After optical DMX (90 channels) polarization beam splitter divides signal to Ox and Oy. Then Y splitter divides optical signal to amplitude and phase analyzer devices.

The amplitude analyzer device works without coherent techniques. Splitter divides fiber on four direction, every with standard IM-DD (Intensity Modulation with Direct Detection) technique. Every detector works with equal clock, but with micro cycle shift and every cycle has 1 or 0 on exit. Then four exits are added providing "amplitude pool" digital signal, which will be upstairs and downstairs. Then special amplitude decoder (with FEC) calculates exactly micro cycle with true 3 bit in true micro cycle.

There are two types of time redundancy. First is for frame synchronization. Every frame consists of 20 micro cycles. First micro cycle we send nothing, without any color. Second and third are useful load, fourth—control summer, which is 5 bits opposite to in second micro cycle. So the total redundancy amounts to 10% and it guarantees exact and quick calculation of contents 1 - 4 micro cycles. After this "start-up" FEC with 10% - 15% redundancy begins "step by step" calculation in past and future may be with Viterby, because our channel is a channel with memory. The total redundancy is 20% - 25%.
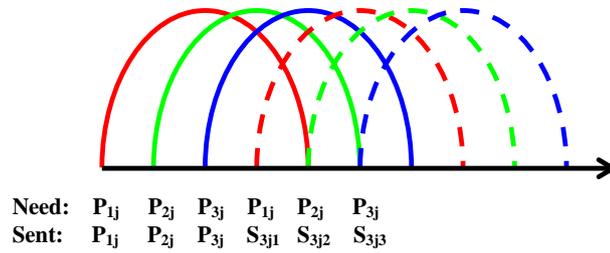
Figure 1. Content is data only with pilots, real transmitted data are pilots and slaves.
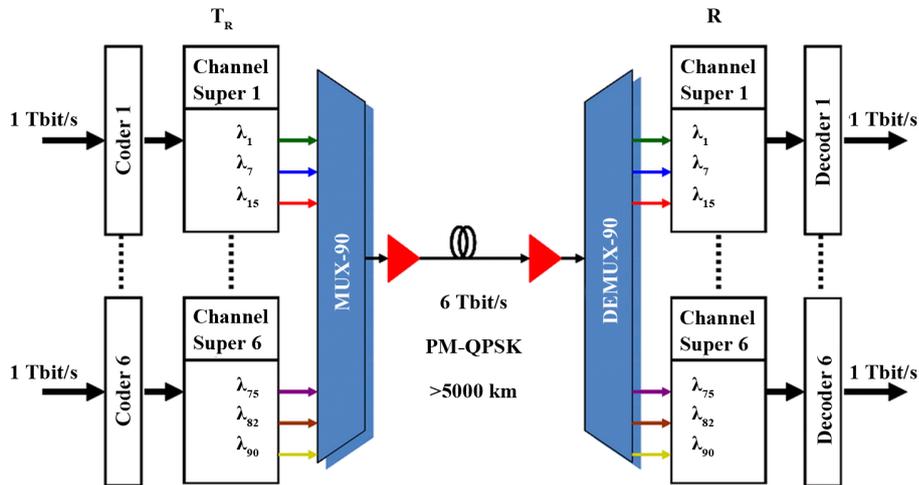
Figure 2. General scheme.
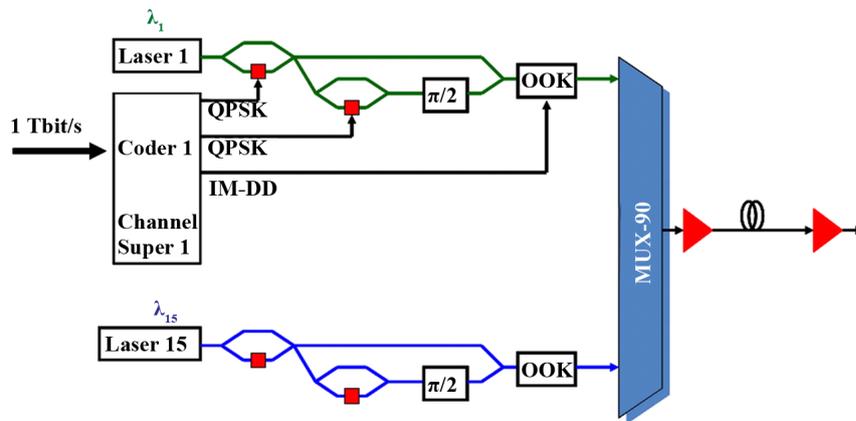
Figure 3. Transmitter in every "channel super".

Table 1. Increasing spectral efficiency with higher order modulation.

| Modulation	Range	Performance in range C (flexible frequency)
PM-BPSK	5000 km	5 Terabit/sec
PM-QPSK	3000 km	10 Terabit/sec
PM-8QAM	1500 km	15 Terabit/sec
PM-16QAM	700 km	20 Terabit/sec
PM-32QAM	350 km	30 Terabit/sec
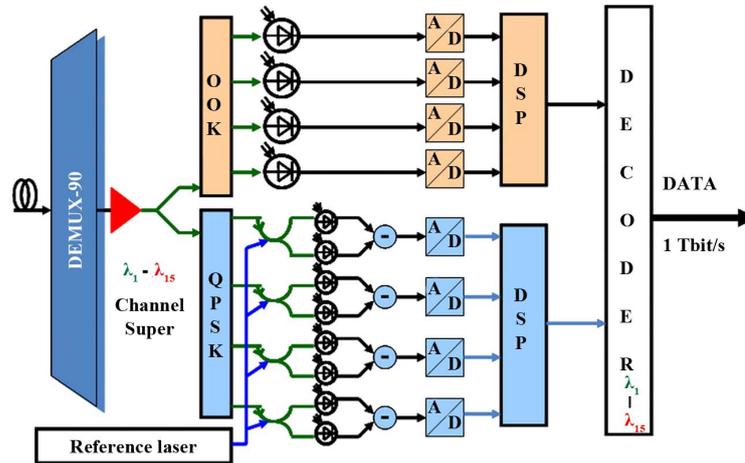
Figure 4. Receiver in every "channel super".

Phase analyzer device works with coherent technique. Reference signal and data signal are sent to four phase detectors, every of which works during cycle with shifting micro cycle. Every such QPSK (of course not differential) detector will receive standard signal (SS) and non standard signal (NSS). SS will be checked by FEC. But we believe that NSS has useful information too. So special phase decoder with FEC will analyse both SS and NSS. Special amplitude decoder and special phase decoder tells each other about amplitude and phase pool in the same time and send out 3 bits and 2 bits in sequence.

Note that there are special mistakes (SM) and real mistakes (RM). SM is the result of decoding real energy (sent by transmitter) in both amplitude and phase decoders. RM is the result of decoding real noise in both amplitude and phase decoders. Many RM (single and may be even more) are deleted without redundancy, because they are in contradiction with pause or received energy as pool. These situations have been investigated in the Institute for Information Transmission Problems [5].

Let us consider several situations on receiver in details after transmitter sent next arbitrary frames:

№	…20	1	2	3	4	5	…	19	20	1	2	3	4
λ		−	P_{1j}	P_{2j}	P_{-1-j}	S_{3j1}	…			−	P_{8j}	P_{7j}	P_{-8-j}

Received data on wavelength P1 in amplitude decoders will be

№	16	17	18	19	20	1	2	3	4	5
λ	−	−	P_{1j}	P_{1j}	P_{1j}	P_{1j}	P_{1j}	P_{1j}	P_{1j}	−

Received data on wavelength P1 in phase decoders will be

?	?	?	?	?	P_{1j}	?	?	?

Received data on wavelength P2-P8, S1-S7 in amplitude decoders may be

20	1	2
	P_2-P_8, S_1-S_7	

Received data on wavelength P1 in phase decoders may be

20	1	2
	P_2-P_8, S_1-S_7	

Thanks to the pause P_{1j} data will be recovered absolutely exactly and quickly in amplitude decoder. P2-P8, S1-S7 will be deleted without redundancy as impossible. P_{1j} data in phase decoder will be recovered using FEC and control summer P-1-j. So our "soft decision" means that we can increase sensitivity in photo detectors in order to improve operation of amplitude detectors without danger of P_2-P_8, S_1-S_7.

Then step by step FEC with redundancy 10% - 15% will recover in future microcycle 5, 6, … and in past 20, 19, 18, … These both data will meet without contradiction.

In addition security of data is extremely high since illegitimate user will be forced to find 15 wavelengths (they are virtual, not adjacent obligatory) among 90, then find pilots and slavers, than status of every pilot and every slave. The number of possible combinations is equal to $90! \approx 10^{135}$, if illegitimate user can on physical level copy 90 channels to memory.

If reach is more than 5000 km significantly, BPSK will be used instead of QPSK. Than over on clock 15 channels have 15 bits, but we 3 due to color + 1 due to phase=4 bit/symbol. During one clock we send $4 \times 4 =$ 16 bit/clock and our power and DRS [6] [7] will be 15/4 = 3.75 times less!

If reach is less than 5000 km (4000 - 5000 km) the number of wavelengths in CS reduced for example 4 pilots + 7 slaves = 11 wavelengths instead of 8 pilots + 7 slaves = 15 wavelengths. Then 88 wavelengths in usual method in theory transmit 8.8 Terabit/sec, but in new 6.4 Terabit/sec, because in every CS every symbol transmits 2 bits due to color and 2 due to QPSK, number of CS = 8. The importance of nonlinear optics remains great because our total power 11/4 = 2.75 times less or 10 lg 2.75 = 4.4 dB.

If reach amounts to 3000 – 4000 km then CS may be 2 pilots and 1 slave. Every symbol transmits 1 bit due to color and 2 bits due to QPSK. Then the total capacity will be 9.

Terabit/sec in both approaches, but in new method total power will be 3/2 = 1.5 times less, number of CS amounts to 30 ($30 \times 3 = 90$). The importance of nonlinear optics is less of course, but not negligible.

If any laser destroys, BER increases from 10 - 15 to 10 - 12 without interruption. Slave S_{33} begins to work instead of destroyed and if S_{31}, S_{32}, S_{33} are necessary together, and then instead of S_{33} we send pause and FEC recover two QPSK bits as deletion.

3. Conclusions

New method of data transmission has been proposed. In usual methods, only one symbol from some varieties is sent and only one symbol will be received-true or false. In new method, only one symbol from some varieties is sent and A LOT of symbol will be received-true or false. Then amplitude analysis provides true color and 3 bits and phase analysis provides true 2 bits.

Reducing DRS (15/4 = 5.74 dB) results in increasing reach of about 1000 km. Over ULH and EULH markets, expected profit of transmission data rate is 2.5 - 3 times more, for example for under sea world. Security of data is extremely high (for existed and future terrestrial market, for any reach—EULH, ULH, long haul and so on). If any laser destroys, BER increases from 10 - 15 to 10 - 12 without interruption.

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