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Optimization in Phase-Encoded, Multiple-Access Metropolitan Area Network

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***Abstract*—This paper presents an optimized formulation for OCDMA based on differential approach and optimal encoding scheme. The development of an optimized OCDMA architecture is addressed and a metropolitan area network (MAN) with optimized system performance is demonstrated. The effect of various noise sources and non-linearity are considered. This optimal solution delivers consistent performance under different scenarios. This work requires minimum medium access control (MAC) supervision and eliminates the need of bulk optics for encoding. This is in line with the requirement of real time delivery for high speed network.**

***Keywords*—optimization; phase encoding; multi-user; metropolitan area network; bit error rate**

I. Background

A metropolitan area networks (MAN) acts as an interconnection between the access network and the long haul network. Thus it is important that a MAN can provide sufficient transmission rate over great distances in order to support multiple users. The network should also be reliable and have good compatibility and flexibility. For short range transmissions with small number of users, the design consideration is less challenging where low laser power, direct modulation, short code length, and short chipping pattern are sufficient to maintain an error free transmission. Access network is the last and first point which connects the users to the network. Conventionally, this network is implemented with twisted pair cooper wires. In order to support higher data rates with the presence of multiple-user access, this aging infrastructure needs to be upgraded. This paper is presents conventional solutions and deficiencies of the network, the optimization of design considerations, and the scalability of the system performance under different design parameters.

II. System Optimization

This section presents four key considerations in system optimization which are:

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a) The conventional multiplexing techniques applied in a multiple-access network, b) the requirement of medium access control (MAC) for traffic managements, c) the deficiency in the conventional approach, and d) the feasibility of optical code division multiple access (OCDMA) technique.

A. *Multi-user Network*

Multiplexing techniques provides cost effectiveness by reducing the number of transmission facilities needed. Through the sharing of common transmission media, multiple users are allowed to access transmission links simultaneously via multiple access schemes. A conventional system adopts several multiplexing techniques, including time division multiplexing (TDM), frequency division multiplexing (FDM), and wavelength division multiplexing (WDM) via time division multiple access (TDMA), frequency division multiple access (FDMA), and wavelength division multiple access (WDMA) [1].

B. *The Requirement of MAC*

Various studies on current traffic management and scheduling schemes have been carried out to improve the system performance [1]&[2]. The studies show that packet contention and wavelength assignments are mainly resolved through MAC monitoring and management. This however increases the complexity of switching and routing architecture. A dynamic wavelength range is required to support additional users. Optical packets transmitted at the same wavelengths and preferred outbound links will contend for a wavelength channel to maintain wavelength continuation.

C. *Merit of OCDMA Technique*

In an OCDMA network, users are identified and distinguished using different codes. OCDMA offers enormous bandwidths with real-time delivery, and provides dynamic and flexible logical network topologies [3]. It introduces fairness among users in accessing shared resources. The flexibility of the code set design allows the switch node to operate in an asynchronous manner. OCDMA can be applied in multiprotocol label switching (MPLS) enabled systems. Optical label is used as an identifier which is carried in the packet header travels along transmission links with a short delay.

D. *Design Issues and Considerations*

Generally, the design issues and considerations in network optimization can be summarized as follows: (i) power consumption, (ii) resource sharing and channel allocation, (iii) routing policies/algorithm, (iv) network throughput, and (v) system performance. Conventionally, in order to support more simultaneous users, longer codes are required in OCDMA system. To date, numerous code set developments have been proposed [4]&[5]to overcome the aforementioned impairments including the system complexity, code set orthogonality, etc. Besides, OCDMA architecture and the associated encoding stage exhibit various deficiencies including rigid synchronization, accuracy issues and stability issues [6]. In this work we will present an optimized solution for a multiple-access MAN which avoids increasing system complexity, and without implementing MAC supervision.

III. Performance Assessment of System in Different systems

This section presents four key areas in the assessment of system performance under different conditions. The four areas include system development, design parameters, intensity modulation-direct detection (IM-DD) and differential approach.

A. System Development

A four-user system is developed as shown in Figure 1 and evaluated under two different conditions: (i) intensity modulation, direct detection and (ii) differential approach. The transmission bit rate tested ranged from 2.5 Gbps to 10 Gbps. A continuous 1552.52 nm wave laser source is used, and a pseudo random binary sequences generator is applied to represent the random traffic pattern in an asynchronous manner. Phase encoding is applied and achieved in the optical domain, and high chipping rate is used to encrypt every bit in the binary stream. The chip length used is twenty with constant code weight [7]. The spread-spectrum sequences used is treated as orthogonal with minimum cross correlation.

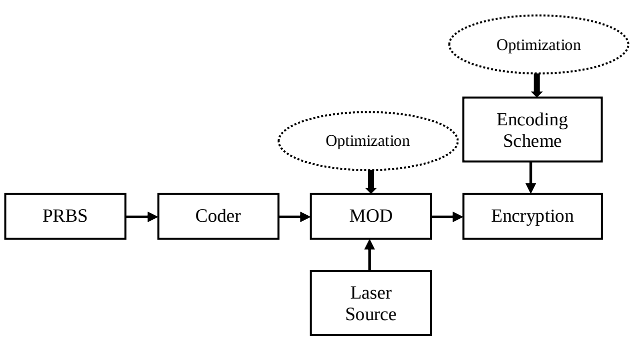

Figure 1. The system architecture and the two key areas of optimization.

B. Design Parameters

The design parameters are the received power, input power and signal-to-noise ratio (SNR). The performance indicators are the bit error rate (BER) and eye diagram. The optical power, optical spectrum, eye diagram are observed too. Multi-user interference (MUI) reduction is applied using a thresholding technique which utilizes the nonlinear effects (self-phase modulation) of the fiber. Noise sources are considered in the BER estimation model including phase induced intensity noise (PIIN), thermal noise and electronic shot noise. The BER estimation model also takes dispersion properties, optical non-linearity and polarization properties into consideration.

C. IM-DD

Pseudo random binary sequences are used to modulate the optical carrier. The output signal is then encoded by fiber Bragg grating based on the encoding scheme. The encoding scheme depends on the spread-spectrum sequences applied. The grating configurations consider the grating type, grating period, refractive index, grating dimensions and the fiber modes, etc. This chipping pattern is imprinted into the fiber core and is used to encrypt the data. The optical spectrum for the encoded signal and decoded signal are observed and shown in Figure. 2. The spectrum has a center frequency of 193.1 THz. In this system, precoding stages and clock recovery stages are not applied. The detection depends on the signal intensity using direct detection. At the receiver, PIN photodiode is used as the detector.

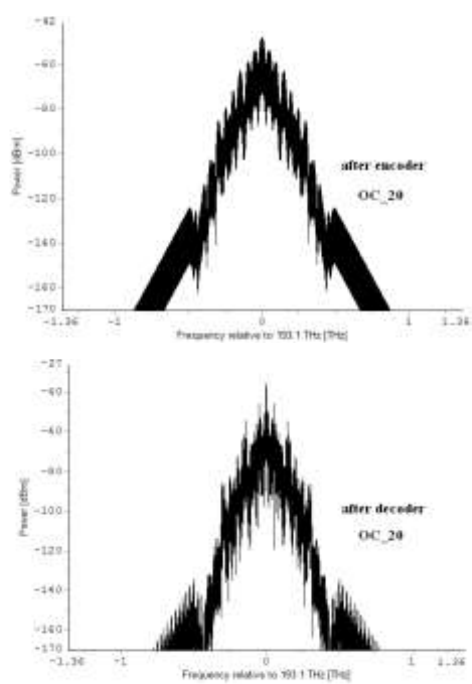

Figure 2. The optical spectrums observed after the encoder and decoder stages before optimization.

The model is evaluated at laser power of 0.04231 dBm and amplifier gain of 20 dB. Phase shift encoding is applied by using time spreading technique as shown in Figure 3. Four users with different unique sequences are demultiplexed after transmitted through a single mode fiber. The encoded signal exhibits an induced peak value of -10.9691 dBm at 5.0083 ns. After multiplexing the signal from four users into the single mode fiber, the signal is then observed before the transmission. At peak power of -11.0791 dBm, three peak values are observed at 4.925 ns, 5.013 ns and 5.051 ns. The maximum optical power measured reduced from -11.0791 dBm to -23.1876 dBm after 40 km of transmission with an attenuation of 12.1085 dB before it is amplified to -3.1876 dBm using a single stage of gain-controlled amplifier. At the receiver end, a 1 × 4 splitter is used to split the power to four channels. The decoded signal shows the presence of MUI and beat noise if system optimization is not applied. In an IM-DD system, the performances of the users are signal intensity dependent.

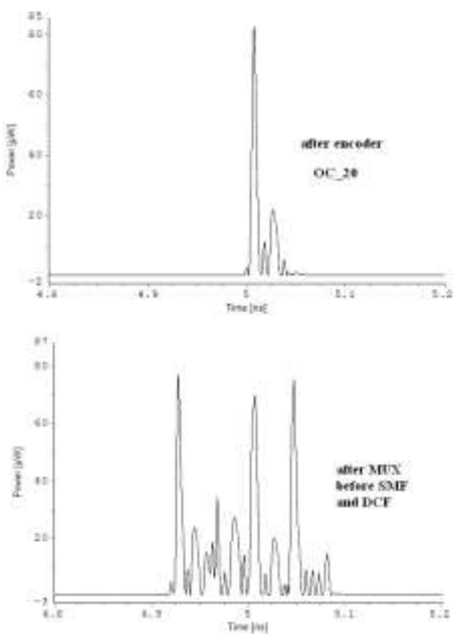

Figure 3. The optical power measured after the encoder and multiplexer before optimization

D. *Differential Approach*

In this system, the binary sequences are precoded before these signals are used to modulate the optical carrier. A Mach-Zehnder modulator configured as phase modulator is used. The optical power can be expressed by equation (1). The phase differences between the two branches, x and y of the modulator are indicated by $\delta\theta_x$ and $\delta\theta_y$ respectively. The modulator should produce low chirp with high extinction ratio.

$$P_{out}(t) = P_{in}(t) \cdot cos^2 \left[\frac{\delta\theta_x(t) - \delta\theta_y(t)}{2}\right] \quad (1)$$

The symmetry factor, k is expressed in equation (2). The output signal is encoded using FBG based on phase encoding. At the receiver, a polarizer and a resampler are used. The maximum dynamic range is set to 50 dB. Clock recovery is required in this stage. The time delay can be estimated via the signal cross correlation without the need of an input reference. Bessel type low pass filter is used and provides low overshoot and ringing effect. PIN photodiode with a sensitivity of 1 A/W is used. The operating temperature is 298 K.

$$k = \frac{\delta\theta_y(t)}{\delta\theta_x(t)} \quad (2)$$

IV. Performance Evaluation

This section presents two key findings: (i) BER over received power and input power, and (ii) BER over MAN distances using eye diagrams. The performances before and after optimization are evaluated. The minimum input power for error free transmission is highlighted, and the maximum allowable transmission distances with BER ≤ 10^{-9} is outlined.

A. *BER over Received/Input Power*

The required received power in dBm in a four-user system using twenty chips is shown in Figure 4. In this IM-DD system, each user is applied with a different pulse center position. The allocation ranges from 0 to 1 relative to the bit frame. Figure 4 demonstrates BER versus received power at input power of 0.04231 dBm measured at 40 km of transmission. Error free transmission of BER ≤ 10^{-9} is not observed. In order to achieve error free transmission, input power greater than 3.9794 dBm is required for user 1 and user 3 as shown in Figure 5 (value displayed in mW). For obtaining the similar performance, input power greater than 6.9897 dBm is required for user 2 and 4. The system is signal intensity and pulse positions dependent, and the performance is not consistent among the users. Some of the encoders are also temperature dependent, leading to system stability issues due to environmental fluctuations.

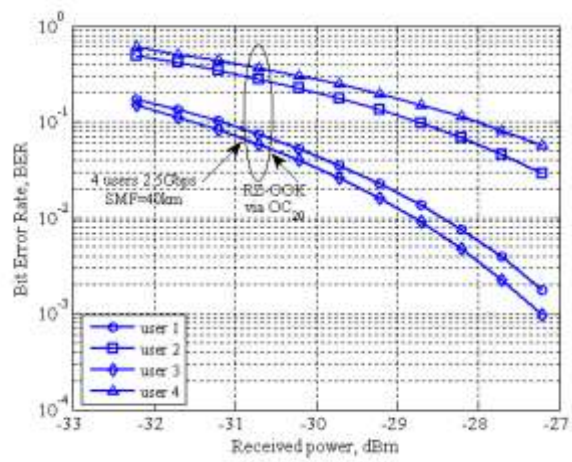

Figure 4. Bit error rate measured over received power in a four-user system at 40 km of transmission before optimization.

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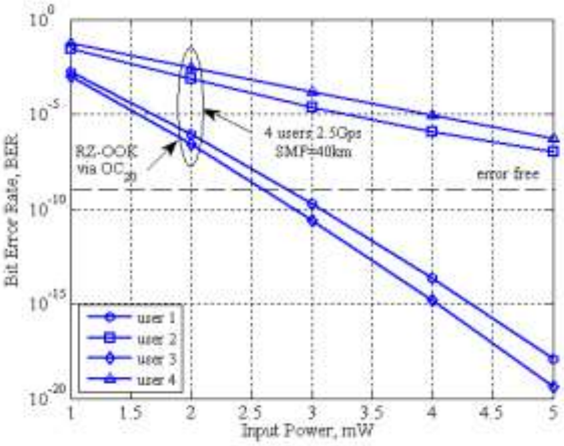

Figure 5. Bit error rate measured over input power in a four-user system at 40 km transmission for error free transmission.

B. BER over MAN Distances

This section presents the allowable transmission distances up to 100 km in a four-user system. The eye diagrams are measured at 100 km of transmission using both IM-DD and differential approach. In an IM-DD system, the maximum allowable distance with error free transmission is limited to 35 km as shown in Figure 6. The performance deterioration is as shown via the eye diagram measurement. The eye closure is due to the high level of beat noise and MUI. The system also encounters jitter and timing issues. The system adopts MUI reduction which is applied after boost amplification prior to transmission.

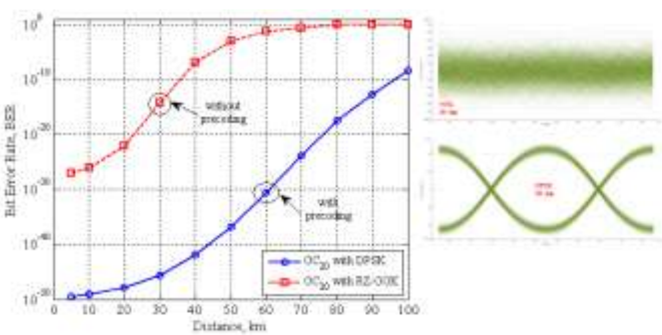

Figure 6. Bit error rate over MAN distances measured in two different systems and the eye diagrams observed in 100 km transmission.

In the differential approach, the maximum allowable transmission distance with error free transmission is extended to 90 km. The precoding stage is applied in the differential approach. The eye height, eye width and eye crossing percentages indicate an ideal timing of the bit stream. The jitter fluctuation due to time deviation is not observed in this approach. Bit one is represented by phase change between the sequential bits, thus, the optical power is relatively constant. This improves the signal quality and system performance, and data can be transmitted in a more robust manner. Differential approach also provides better tolerance to non-linear effect and cross talk.

The demodulation depends on the phase changes of the received signal. Thus, the system does not require a rigid reference signal. Such flexibility eases the facility of an optimized MAN design.

V. CONCLUSION

This paper presents the optimization achieved in a phase encoded multi-access MAN. Three keys aspects are reviewed: the conventional approaches and deficiencies, the optimization issues and design considerations, and the scalability of the system performance under different design parameters. Several multiple access techniques are outlined. The merits of OCDMA techniques are highlighted and various design considerations in MAN optimization are discussed.

This paper also demonstrates the system development and assesses the system performance under different system configurations. The optical spectrum, encode/decode signal and eye diagrams are observed. The bit error rate over received power, input power and transmission distance are measured. The attainment of error free transmission is demonstrated in a four-user system. The extension of transmission distance without complicating the system architecture is outlined in an optimized MAN. In this case, amplification stage, MUI reduction and phase encoding schemes are applied. Comparative study before and after optimization is highlighted too. Such system requires minimum level of MAC supervision which makes it one step closer to the realization future high speed ultra-fast, Terabits network.

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