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Future optical networks: An optimised implementation of differential quadrature phase shift keying modulation format

L. H. LEE[a], T. K. GEOK[a], A. W. REZA[b*]
[a]*Faculty of Engineering & Technology, Multimedia University, Jalan Ayer Keroh Lama, Bukit Beruang, 75450 Melaka, Malaysia*
[b]*Faculty of Engineering, Department of Electrical Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia*

This study proposes an optimised implementation of a differential quadrature phase shift keying (DQPSK) modulation format. The DQPSK scheme is an external modulation format, where modulators are needed for the generation of the optical signal for transmission. In this paper, the performance comparison between the conventional DQPSK modulation format and the optimised DQPSK modulation format is investigated. The obtained results and analysis show that the optimised DQPSK modulation format can achieve better performance as compared to the conventional DQPSK modulation format in terms of transmission distance. The technique presented in this study can help to increase the bandwidth and the speed of the optical fiber while maintaining the existing fiber cable and network facilities. This study can also assist the service providers to supply high-speed broadband services to the rural areas, which are located very far away from the central office.

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1. Introduction

Fiber to the Home (FTTH), only able to reach its mature stage when new forms of technology are being developed that will able to deliver substantial cost reduction across the board and facilitate a transition from metal to optical cable systems. The FTTH needs advancement in ranges from hardware, such as optical cables, transmission system components, etc to non-hardware items, such as operation and maintenance, design, and construction. As a result, in the beginning of employment of the fiber as transmission medium, the cost per unit subscriber of optical access system was six to eight times greater than that for access via conventional metal wire [1][2].

As time goes on and advances in technology and hardware, the cost of using fiber had been reduced to approximately double for that metal wire. Finally, in the recent year, the cost was about the same. This had made possible of all metal wires be replaced by the fiber optics when aging become an issue. The optical access network can also be extended to metal wires where upgrading of aging metal cable equipment is needed.

The cost reduction objectives can be achieved through the five key concepts as follows:

(i) new approach of network design,
(ii) low cost of optical PDS (passive double star),
(iii) low cost of optical fiber cables and related technology,
(iv) simple implementation and maintenance, and
(v) optical operation systems.

Before FTTH was able to realize, a pie system was the first been implemented, which mainly involved attaching an optical access network onto an existing metal-wire telephone infrastructure. In this way, the cost reduction can be achieved while maintaining the speed of the line, before upgrading is necessary to replace the metal wires.

When the demand increases, the customers who use the FTTH have the volume to cover the cost of the implementation; thus, metal wires can be replaced by the fiber optics to provide higher speed and bandwidth to the customers. However, another issue with the FTTH service is so-called “regional disparities” where FTTH services are confined to bigger cities and their immediate surroundings, with little penetration into rural areas. Thus, in this paper, we propose the optimised differential quadrature phase shift keying (DQPSK) modulation format with the aim to penetrate into rural areas by breaking the transmission distance limit imposed by the conventional modulation formats [3]-[14], such as NRZ-OOK (non-return-to-zero on-off keying) modulation format, the conventional DQPSK modulation format, and etc.

The ultimate objective of communication is to demolish the barrier of time and distance, where video and related technology can be provided with more natural way. Real time communication has not been possible with narrowband communications. Breaking through the time barrier means people will have more free time while breaking through distance means individual and corporations will able to expand their sphere of activities. This in turn promotes human activities in a global scale, transcending national and regional boundaries as well as in industries and generations. High-speed communications enable knowledge and wisdom to be shared among individuals, companies, and borderless business operations. Thus, individual and corporation can access knowledge and information around the world. Ultimately, this will revolutionise the way we live and the way we do business.

The key requirements of the access network are economy, good performance, and ease of use for both the installation technicians and customers. The primary development objective for optical access network is the cost efficiency, easiness of handling, and network capacity. It is possible to boost the cost-effectiveness and performance further by utilising the broad optical wavelength domain of optical transmission via techniques, such as wavelength division multiplexing (WDM) technology, which increases the transmission capacity by transmitting multiple wavelengths through a single fiber. For the ease of use, the access network can be designed to utilise the existing networks and facilities, thus minimise the installation cost. Moreover, it makes easier to introduce and add new services.

With the need to increase the capacity of the optical transmission system, there is an increased research interest in multi-valued phase signaling, particularly in DQPSK [15]. The DQPSK is a quaternary phase modulation format, which offers greater spectral efficiency with larger dispersion tolerance compared to the binary formats, such as intensity (IM-OOK) modulation format or duobinary modulation format. As a quaternary modulation format, DQPSK transmits 2 bits per symbol as opposed to only 1 bit per symbol for the binary formats [16]. In the development of future optical networks, there is a strong demand to cut down the costs per bit. Thus, DQPSK has drawn high attention as this modulation format doubles the data rate without changing the symbol rate, resulting in higher spectral efficiency and relaxed the component requirement [17]. The optical DQPSK offers better tolerance to chromatic dispersion and polarisation mode dispersion (PMD), together with the increased spectral efficiency [18].

By implementing more efficient modulation format as we propose, only transmitter and receiver part will be altered; and transmitting component, especially the optical fiber can be reused for higher efficiency transmission. Thus, the cost can be cut down without replacing the existing fiber cables. In other words, more bits can be transmitted using the same existing optical fiber, by just replacing the transmitter and receiver according to different modulation formats.

In this study, we investigate how modulation techniques can help to increase the bandwidth and speed of the optical fiber while maintaining the existing fiber cable and network facilities. Thus, we propose an optimised DQPSK modulation format to improve the existing conventional DQPSK modulation format through an increase of transmission distance in fiber optics. The remaining part of this paper is organised as follows. In Section 2, the setup of the optimised and the conventional DQPSK modulation formats are included. In Section 3, we will present the simulation results for single channel repeaterless transmission of DQPSK and will show how parametric optimisation is done. The performance comparison between the conventional DQPSK modulation format and the optimised DQPSK modulation format is investigated here. Finally, Section 4 provides the concluding remarks.

2. Methodology

2.1 Proposed optimised DQPSK setup

We propose an enhanced modulation scheme, known as optimised DQPSK modulation format. This optimised DQPSK modulation format is implemented through the optimisation of the parameters used in the existing conventional DQPSK modulation format. Figure 1 shows the schematic setup for the implementation of the optimised DQPSK modulation format. As outlined in the following figure, it shows the basic design of the optimised DQPSK modulation system setup that consists of two single-arm Mach-Zehnder Modulators (MZMs) together with a phase modulator. According to the basic design, the phase modulation of 0 and Π with I-electrical signals or Q-electrical signals are realised by driving each MZM at each null-bias point. After combining the two modulated light with Π/2 phase shift in the MZMs, the 4-level phase modulation of 0, Π/2, Π, and 3Π/2 is obtained. As each symbol transmits 2 bits of information, the symbol rate is equal to half of the total bit rate *B* [19]. Through transmitting 2 bits/symbol at the reduced clock rate, the DQPSK can realise a number of advantages compared to the binary on-off keying and duobinary modulation formats.

The precoder is also another important element in our system setup. It provides quadrature phase control to maintain an optical phase difference of Π/2 between upper and lower arms of the MZMs, ensuring quadrature addition of the optical fields on recombination. After the appropriate modulation done on the transmitter, the optical signals are coupled into fiber optic cables. At the receiver side, a pair of balanced optical detector is employed for the optical signal detection. Each pair of detector has a bandwidth commensurate with a symbol rate *B*/2. The electrical signal produced by the detectors is then fetched to analyser for further data analysis. The results obtained will be used for comparison that will be discussed in later sessions.

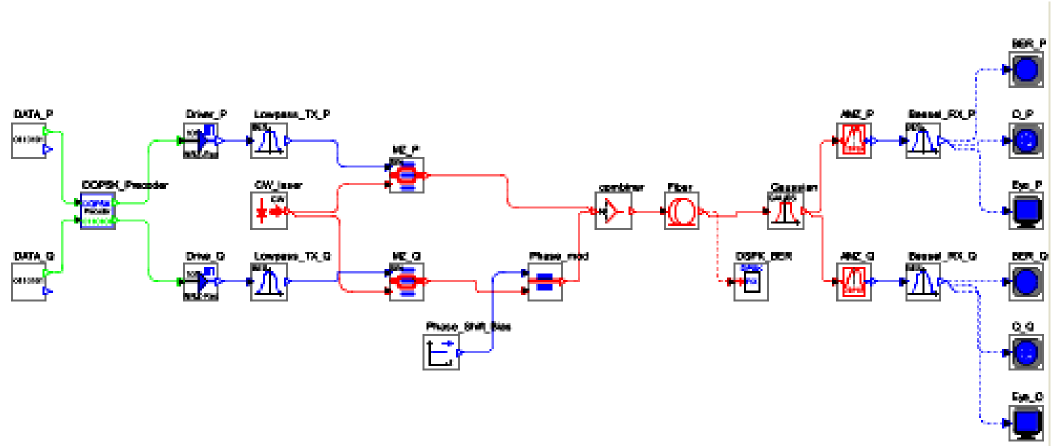


Fig. 1. Schematic setup for the optimised DQPSK modulation format.

2.2 Conventional DQPSK modulation format setup

Fig. 2 shows the schematic setup of the conventional DQPSK modulation format. The schematic setup of Fig. 2 has not much of difference with respect to Fig. 1. In the conventional DQPSK setup, the DQPSK modulator consists of two single-arm MZMs and a phase modulator as seen in Fig. l. These modulators are combined together to form a compound component. The signal generation and detection are similar to the above section. The conventional DQPSK modulation format is presented here as a reference for the optimised DQPSK modulation format with the purpose of comparison in terms of their performance characteristics. For the purpose of comparison between the optimised DQPSK and the conventional DQPSK modulation format, certain optical components will share the same parameter value, the most prominent example is the optical fiber, while other components might have different values, such as MZMs, phase modulators, and balanced receiver in order to perform at its optimum stage. The optical component parameters will be shown in the following section.

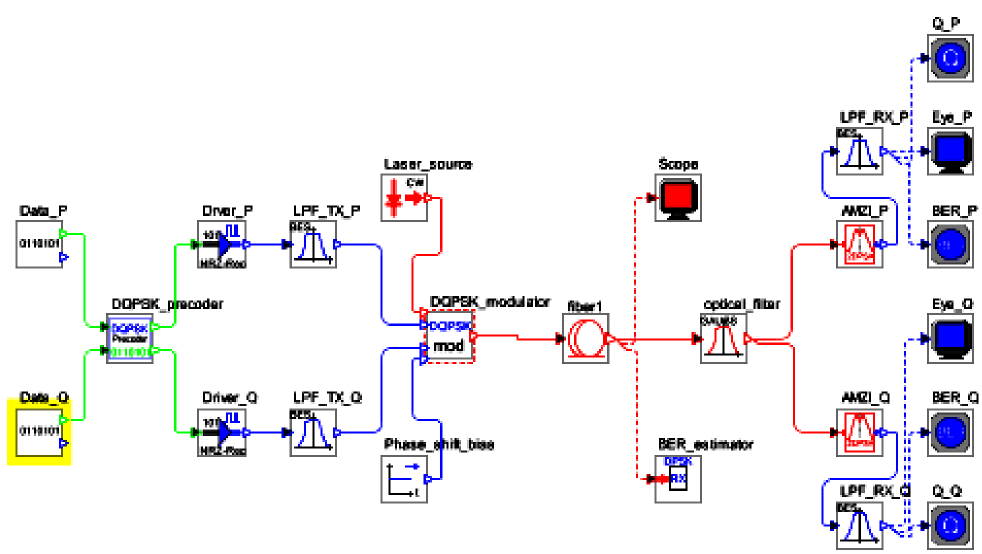


Fig. 2. Schematic setup for the conventional DQPSK modulation format.

2.3 Modeling

The above two simulation models, namely, the optimised DQPSK modulation format and the conventional DQPSK modulation format are used to simulate a single channel optical communication link. In the optimised DQPSK simulation model, the component parameters of the transmitter and the receiver are optimised (the optimised parameter values will be presented in the following section). While for the conventional DQPSK simulation model, the component parameters used is the typical value available from Optsim^{TM} library. However, these two simulation models will still share the same component parameter, especially the fiber optic. The shared component parameters will be listed in the table of the following section.

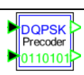
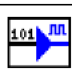
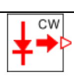
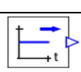
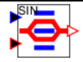
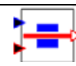
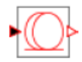
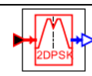
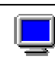
The performance of these models is monitored by comparing the bit-error-rate (BER), eye diagram, and Q value at the receiver end [11]. The target performance is set to BER=10 $^{-9}$, which is the typical error rate for the optical fiber telecommunication. By plotting the diagram of BER versus distance travelled, the value of distance (corresponds to BER= 10 $^{-9}$) is the maximum achievable distance that the signal can travel without using any repeater or amplifier. Thus, from the results analysis, we can compare the performance of each modulation format and judge which one is performing better than the others.

3. System model and parameter

3.1 System model components for the optimised and the conventional DQPSK modulation formats

Table 1 shows all the components (symbol, name, and description) used in the simulation for the optimised and the conventional DQPSK modulation formats.

Table 1. Components used for the optimised and the conventional DQPSK modulation formats.

Component Symbol	Component name	Description
	Data Source	Simulates a pseudo-random bit sequence or a deterministic logical signal generator of arbitrary level.
	DQPSK Precoder	Generates a signal whose phase is digitally modulated in the DQPSK format.
	NRZ driver	Implements the non-return-to-zero rectangular driver; convert the logical data into electrical signal.
	Electrical Bessel Filter	This component simulates an electrical filter. This component implements low-pass, high-pass, and band-pass Bessel filters.
	Continuous-Wave Lorentzian Laser (CW laser)	This model implements a simplified continuous wave laser. Laser phase noise is taken account by generating a Lorentzian emission line shape, whose FWHM is specified by the parameters.
	Bias Signal Generator	This component simulates a generator of constant level signal.
	Sin^2 Amplitude Modulator	This model implements a single arm Mach-Zehnder Amplitude Modulator with sin^2 electrical shaped Input-Output P-V characteristic.
	Optical Phase Modulator	This component simulates a phase modulator, i.e. a component that changes the phase of the input optical signal as a function of the electrical driving voltage.
	Optical Fiber Link	This component models the propagation of the optical signal along an optical fiber span.
	Ideal Balanced Receiver	The balanced receiver is composed of a tunable Mach-Zehnder interferometer having two optical output ports. In the interferometer, optical paths differ by a delay τ that must be set equal to the bit time duration. Each optical output is detected by an ideal PIN photodetector, and the output electrical signal is the difference between the detected currents.
	Optical Power Meter	Measures the power (mean square value) of an optical signal.
	Electrical Q Estimator	Measures the Q value. Besides the Q value, the following information are provided: optimal threshold, eye closure, average eye opening, eye opening, tolerance to sampling instant variation, jitter measurement for RZ signal, diagram of Q value versus sampling instant, and diagram of eye closure versus sampling instant.
	Electrical Scope	Simulates an oscilloscope for electrical signals. It collects data for diagrams, such as amplitude, eye diagram, histogram at the optimum sampling instant, and power spectrum of the electrical signal.
	BER Estimator	This component estimates the Bit Error Rate (BER) of an electrical signal.

3.2 Shared component parameters for the optimised and the conventional DQPSK modulation formats

Table 2 shows the shared component parameters used in the modulation formats of the optimised DQPSK and the conventional DQPSK.

The purpose of the shared component parameters is to increase the cost efficiency. The optimised DQPSK and the conventional DQPSK modulation formats have different characteristics and also have different performances e.g., the conventional DQPSK modulation format travels shorter distance compared to the optimised DQPSK modulation format. Thus, when perform system tuning for the optimisation process, most of the components will be maintained, such as laser source, NRZ precoder, Bessel filter, and etc.

Through the reuse of the shared component parameters, the cost efficiency can be achieved. The cost saving can also be done when continuing the service of the existing optical components and infrastructures, and one of the prominent examples is the optical fiber, as this fiber cables are usually laid out over long distance across continents. Another reasonable reason for using the shared component parameters is to show a fair comparison in terms of the analysis and results obtained.

Table 2. Shared component parameters for the optimised and the conventional DQPSK modulation formats.

Data Source	5Gbps, with word length of PRBS of 2^7-1
NRZ precoder	Upper level: +5V Lower level : -5V
Electrical Bessel Filter	Number of poles: 5 -3dB bandwidth: 5GHz
Standard single-mode fiber (SSMF)	Attenuation: 0.2 dB/km Zero Dispersion Wavelength: 1391.5 nm Dispersion Slope at 1550nm: 0.07 [ps/nm^2/km] Dispersion at 1550nm: 16 ps/nm/km Reference Frequency: 193.4 THz
CW laser	Center emission wavelength: 1550nm Optical launching power: 0dBm

3.3 Parameter values for the optimised DQPSK modulation format

Table 3 lists some of the parameter values used for the optimised DQPSK modulation format. The parameter values used in optimised DQPSK modulation format are different compared to the typical parameter values used for the conventional DQPSK modulation format.

Table 3. Component parameters for the optimised DQPSK modulation format.

Single-arm Mach-Zehnder Amplitude Modulator (Sin^2 MZM)	Maximum Transmissivity offset voltage: 5V Extinction Ratio: 20dB $V\pi$ =5V Chirp Factor : 0dB Average power reduction due to modulation: 3dB -3dB bandwidth: 5GHz
Bias Signal	Phase shift bias : 2.5 AU
Phase modulator	Zero phase voltage : 0V Excess loss: 3dB $V\pi$ =5V
Balanced Receiver	Center frequency: 194.00062 THz

4. Results and discussion

4.1. Results for the conventional DQPSK modulation format

As mentioned in the above paragraphs, the results generated for the conventional DQPSK modulation format is for the purpose of the performance comparison. Thus, it is deemed as a reference point when the comparison of the optimised DQPSK modulation format is performed.

The diagram of BER versus distance transmitted of the conventional DQPSK modulation format is plotted in Fig. 3. At the desired BER of 10^{-9}, it corresponds to the transmission distance of 160km. The transmitted signal is severely distorted after 160km and it will not be accepted in our communication link. The thresholds BER for all the modulation formats are set to 1×10^{-9} as this BER value is the typical error rate for most of the optical fiber communication systems [4]. Note that, the conventional DQPSK modulation format is capable of achieving 160km of transmission distance, which is certainly better than the existing NRZ-OOK or conventional duobinary modulation format; however, in terms of implementation of DQPSK modulation format, it is sometimes quite complicated as there are number of modulators and components needed for the implementation.

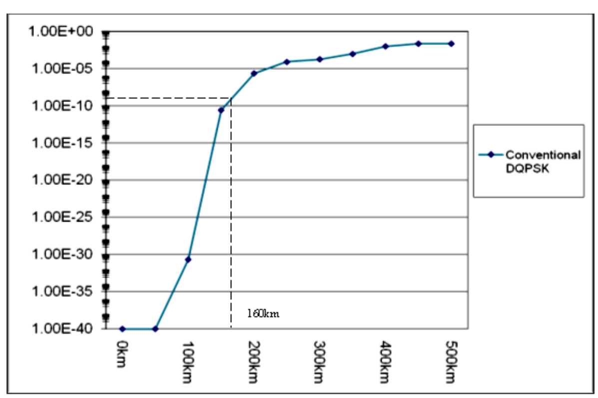


Fig. 3. BER versus distance (km) for the conventional DQPSK modulation format.

In the following, the eye diagrams of the conventional DQPSK modulation format are shown in Fig. 4.

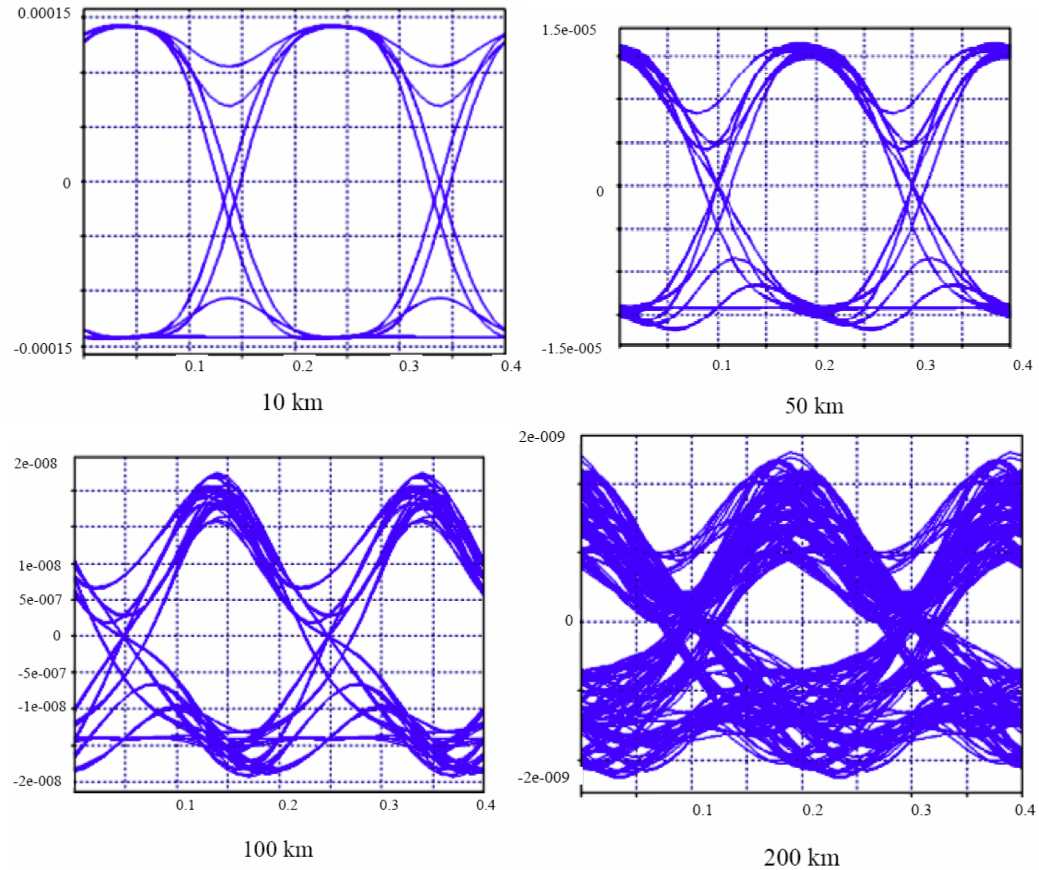


Fig. 4. Eye diagram of the conventional DQPSK modulation format at (a) 10km; (b) 50km; (c) 100km; (d) 200km.

Fig. 4 shows the received signal of the eye diagram of the conventional DQPSK modulation format at 10km, 50km, 100km, and 200km. At 10km and 50km of transmission distance, the eye opening is wide and easy to distinguish. At 100km, the eye diagram of this conventional DQPSK modulation format starts showing indistinct pattern, noise is noticeable at the upper and lower levels of the eye diagram; however, the eye opening still can be distinguished. At 200km, the eye opening is severely distorted and difficult to be distinguished. Thus, from the eye diagram analysis, the performance of an optical network system setup can also be justified.

4.2 Results for the optimised DQPSK modulation format

The diagram of BER versus distance transmitted of the optimised DQPSK modulation format is plotted in Fig. 5.

At the desired BER of 10^{-9}, the proposed system corresponds to 400km of transmission. The transmission further than this distance will not comply with the communication link requirement. The thresholds BER for all the modulation formats are set to 1×10^{-9} as this BER value is the typical error rate for most of the optical fiber communication systems [4] as stated earlier. It is noted that the optimised DQPSK modulation format is capable of delivering signals up to a distance of 400km, thus, if the access network link covers the radius of 400km, this optimised DQPSK modulation format can be taken into consideration. The eye diagrams for the optimised DQPSK modulation format are shown in Fig. 6.

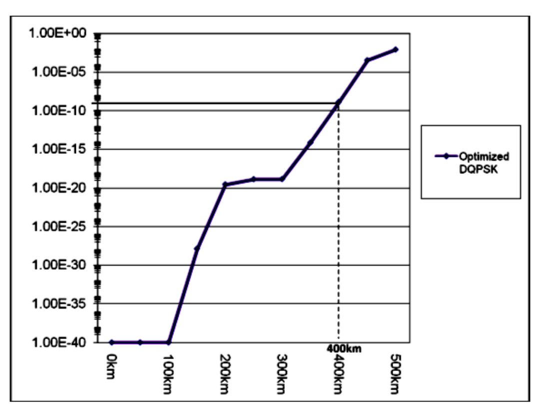


Fig. 5. BER versus distance (km) for the optimised DQPSK modulation format.

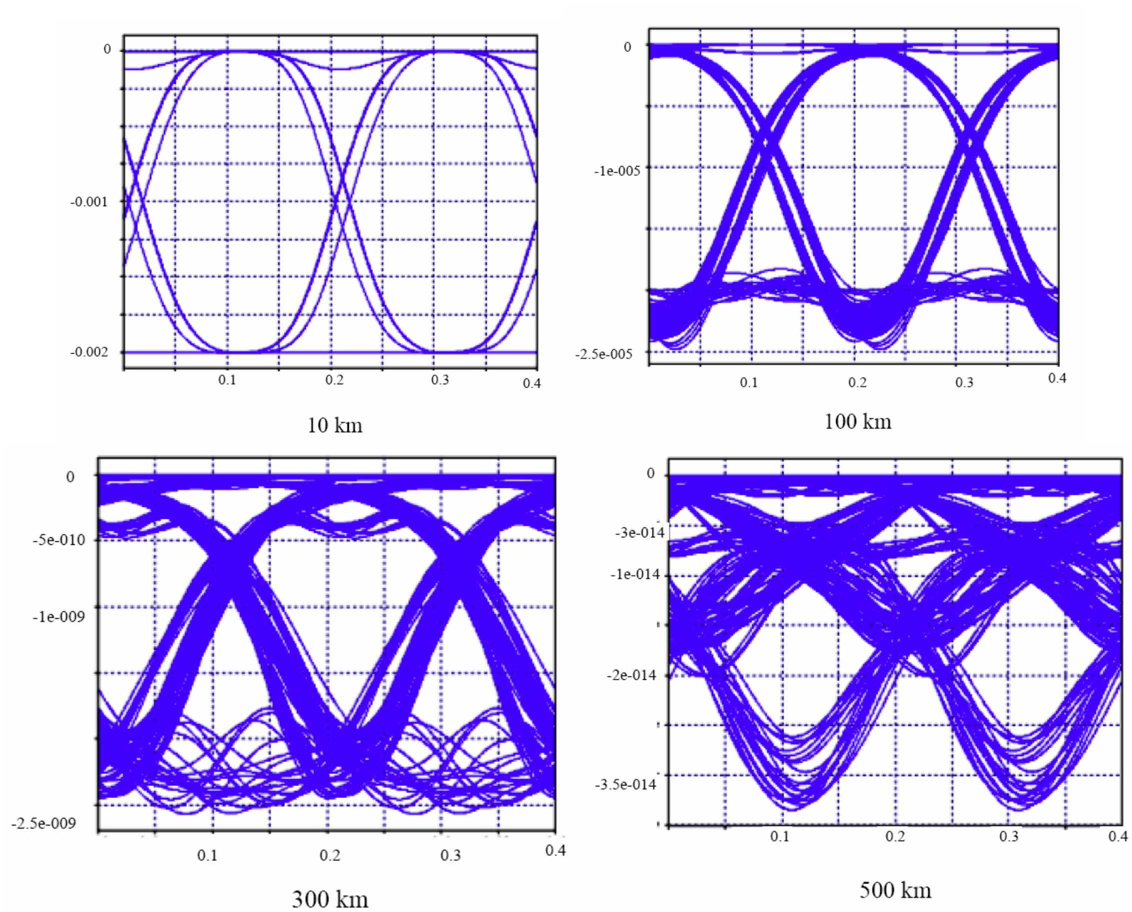


Fig. 6. Eye diagram of the optimised DQPSK modulation format at (a) 10km; (b) 100km; (c) 300km; (d) 500km.

Fig. 6 shows the received signal of the eye diagram of the optimised DQPSK modulation format at 10km, 100km, 300km, and 500km, respectively. At 10km of transmission distance, the eye opening is wide and easy to distinguish. At 100km, the eye diagram of this optimised DQPSK modulation format still clearly depicted, however, noise is noticeable at the lower levels of the eye diagram. At 300km, the eye diagram starts showing the indistinct pattern, where the lower level of the eye diagram stars accumulating higher level of noise; however, the eye opening still can be determined. At 500km, the eye opening is severely distorted where high noise level accumulating at the upper and lower part of the eye diagram. Thus, from the eye diagram analysis, the performance of an optical network system setup can also be justified.

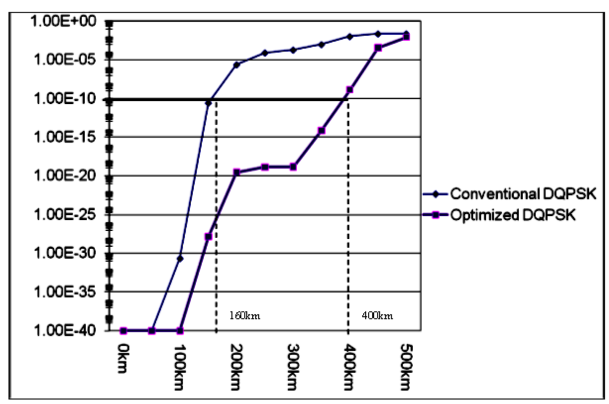


Fig. 7. BER versus transmission distance (km) with the conventional DQPSK and the optimised DQPSK modulation format.

4.3 Results analysis for the conventional DQPSK and the optimised DQPSK

Fig. 7 shows performance comparison of the conventional DQPSK and the optimised DQPSK modulation format, in terms of BER versus transmission distance (km).

Actually, the results of BER versus transmission distance in above sections are combined and then presented in Fig. 7. The purpose of combining the results into Fig. 7 is for the ease of data analysis and comparison. From the results obtained from the above sections and Fig. 7, it can be noticed that the maximum distance achieved by the optimised DQPSK modulation format is 400km. It is also observed that the transmission distance is limited to 160km under conventional DQPSK modulation format. Drawn to the conclusion from the results analysis, the optimised DQPSK modulation format has shown improvement of 60% over the conventional DQPSK modulation format at a given BER = 1 $\times 10^{-9}$. Consequently, by optimising the component parameters as mentioned above to the transmission system without any modification of the existing fiber facilities, improvement can be achieved in terms of transmission distance. This improvement in the transmission distance can solve the problem faced by the current service providers to provide high-speed network to the rural areas. In other words, the rural areas which are located far away from the central offices can still able to enjoy the high-speed broadband, provided by the service providers through the improvement of the transmission distance using the proposed optimised DQPSK modulation format.

It is further observed from the results analysis, when designing the optical transmission system, the designers will choose which type of modulation format is to be applied in the system depending on the access network link coverage. The designer will also consider the cost efficient factor when implementing the system. For the rural area located very far from the central office, such as a distance of 350km, this optimised DQPSK can be implemented to provide broadband services to that area.

5. Conclusions

This study has successfully demonstrated that the optimised DQPSK modulation format can achieve better results compared to the conventional DQPSK modulation format in terms of the transmission distance. The results reveal that the optimised DQPSK modulation format can significantly improve the transmission distance by 60% over the conventional DQPSK modulation format at a given BER = 10^{-9}. This study can also assist the service providers to supply high-speed broadband services to the rural areas, which are located very far away from the central office. For the optimised DQPSK, less maintenance is required along its propagation path as no electrical power is needed, since there are no active components involved, such as amplifiers or regenerators, which also make the system cost effective.

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*Corresponding author: awreza98@yahoo.com