Latency causes and reduction in optical metro networks

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ABSTRACT

The dramatic growth of transmitted information in fiber optical networks is leading to a concern about the network latency for high-speed reliable services like financial transactions, telemedicine, virtual and augmented reality, surveillance, and other applications. In order to ensure effective latency engineering, the delay variability needs to be accurately monitored and measured, in order to control it. This paper in brief describes causes of latency in fiber optical metro networks. Several available latency reduction techniques and solutions are also discussed, namely concerning usage of different chromatic dispersion compensation methods, low-latency amplifiers, optical fibers as well as other network elements.

Keywords: Latency, optical networks, time delay, metro networks

1. INTRODUCTION

Internet traffic is growing very fast. Based on Cisco Visual Networking Index (VNI) forecast, global IP traffic has increased more than fourfold in the past 5 years, and will increase threefold over the next 5 years. It will reach 1 zettabyte (ZB) per year or 83.8 exabytes (EB) per month in year 2015. Metro traffic will exceed long-haul traffic in year 2014, and will account for 58 percent of total global IP traffic by year 2017.²

![Figure 1. Metro and long-haul total IP traffic comparison by years.](image)

Figure 1 clearly shows that traffic from metro networks is growing nearly twice as fast as long-haul traffic from year 2012 to year 2017. Metro traffic growth is higher because role of content delivery networks are increasing more and more, respectively long-haul links are bypassed and traffic is delivered via metro and regional backbones.¹ Also, metro networks are filling the gap between access and long distance fiber optical networks.²

The more information we are transmitting the more we need to think about parameters like available bandwidth and latency. Bandwidth is usually understood by end-users as the important indicator and measure of network performance. It is surely a reliable figure of merit, but it mainly depends on the characteristics of the equipment. Unlike bandwidth, latency and jitter depend on the specific context of transmission network topology and traffic conditions. As network latency we understand delay from the time of packet transmission at the sender to the end of packet reception at the

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receiver.\(^3\) If latency is too high it spreads data packets over the time and can create an impression that an optical metro network is not operating at data transmission speed which was expected. Data packets are still being transported at the same bit rate but due to latency they are delayed and affect the overall transmission system performance.\(^4\)

It should be pointed out, that there is need for low latency optical networks in almost all industries where any data transmission is realized. It is becoming a critical requirement for a wide set of applications like financial transactions, videoconferencing, gaming, telemedicine and cloud services which requires transmission line with almost no delay performance. These industries are summarized\(^5,6\) and shown in table below, please see Table 1.

<table>
<thead>
<tr>
<th>Industry</th>
<th>Applications and services</th>
</tr>
</thead>
<tbody>
<tr>
<td>Education</td>
<td>• video conferencing&lt;br&gt;• live-streaming&lt;br&gt;• rich learning content&lt;br&gt;• dynamic e-learning platforms&lt;br&gt;• presentation applications&lt;br&gt;• dynamic administration tools&lt;br&gt;• cloud-based applications</td>
</tr>
<tr>
<td>Healthcare</td>
<td>• Picture Archiving Communications Systems (PACS)&lt;br&gt;• telemedicine, telehealth applications&lt;br&gt;• diagnostic imaging&lt;br&gt;• Electronic Medical Records (EMR)&lt;br&gt;• patient portals&lt;br&gt;• mobile healthcare applications and equipment</td>
</tr>
<tr>
<td>Media and Entertainment</td>
<td>• live-streaming breaking news&lt;br&gt;• television shows&lt;br&gt;• videoconferencing&lt;br&gt;• movies over Internet&lt;br&gt;• transfer large files, images, and videos from the field to studios around the world&lt;br&gt;• real-time gaming</td>
</tr>
<tr>
<td>Government</td>
<td>• interaction between communities and their governments&lt;br&gt;• transportation management&lt;br&gt;• emergency response and general commerce&lt;br&gt;• circulation of documents&lt;br&gt;• self-service portals</td>
</tr>
<tr>
<td>Legal</td>
<td>• sharing large, bandwidth-intensive files quickly and securely&lt;br&gt;• secure and high speed access to critical files &quot;24 hours a day, 7 days a week&quot;</td>
</tr>
<tr>
<td>Finance</td>
<td>• High-Frequency Trading (HFT) and high speed information exchange&lt;br&gt;• financial transactions&lt;br&gt;• connections to brokers, dealers, exchanges, hedge funds and information feeds</td>
</tr>
</tbody>
</table>

In fiber optical networks latency consists of three main components which adds extra time delay: the optical fiber itself, optical components, and opto-electrical components. Therefore, for the service provider it is extremely important to choose best network components and think on efficient low latency transport strategy.\(^7,8\)

There are many researches about improvement of transmission speed in fiber optical metro networks while impact and sources of latency is not yet investigated sufficiently. As mentioned before, latency is a critical requirement for a wide set of applications. Even latency of 250 ns can make the difference between winning and losing a trade.\(^9\) Surely "latency reduction" is among the hot key-words for vendors, end-users and telecommunication service providers. According to a recent market analysis, the request for ultra-low latency services is increasing dramatically and opening many opportunities especially in the field of end-to-end high-speed optical services.\(^10\) Latency reduction is very important in financial sector, for example, in the stock exchange market where 10 ms of latency could potentially result in a 10% drop in revenues for a company.\(^3\) No matter how fast you can execute a trade command, if your market data is delayed relative to competing traders, you will not achieve the expected fill rates and your revenue will drop.\(^11\) Low latency trading has moved from executing a transaction within several seconds to milliseconds, microseconds, and now even to
nanoseconds. Nowadays, a millisecond improvement in network speeds offers competitive advantage for financial institutions. In this paper we will discuss the importance and sources of latency in optical metro networks as well as describe potential solutions for its reduction and give a latency calculation example to clearly explain low-latency issue to the reader.

2. LATENCY SOURCES IN OPTICAL NETWORKS

It is important to look at latency as consisting of many different components. Latency is a time delay experienced in system and it describes how long it takes for data to get from transmission side to receiver side. In a fiber optical communication systems it is essentially the length of optical fiber divided by the speed of light in fiber core, supplemented with delay induced by optical and electro optical elements plus any extra processing time required by system, also called overhead. Signal processing delay can be reduced by using parallel processing based on large scale integration CMOS technologies.

Added to the latency due to propagation in the fiber, there are other path building blocks that affect the total data transport time. These elements include opto-electrical conversion, switching and routing, signal regeneration, amplification, chromatic dispersion (CD) compensation, polarization mode dispersion (PMD) compensation, data packing, digital signal processing (DSP), protocols and addition forward error correction (FEC). Data transmission speed over optical metro network must be carefully chosen. If we upgrade 2.5 Gbit/s link to 10 Gbit/s link then CD compensation or amplification may be necessary, but it also will increase overall latency. For optical lines with transmission speed more than 10 Gbit/s (e.g. 40 Gbit/s) a need for coherent detection arises. In coherent detection systems CD can be electrically compensated using DSP which also adds latency. Therefore, some companies avoid using coherent detection for their low-latency network solutions.

From the standpoint of personal communications, effective dialogue requires latency < 200 ms, an echo needs > 80 ms to be distinguished from its source, remote music lessons require latency < 20 ms, and remote performance < 5 ms. It has been reported that in virtual environments, human beings can detect latencies as low as 10 to 20 ms. In trading industry or in telehealth every microsecond matters. But in all cases, the lower latency we can get the better system performance will be.

2.1 Single mode optical fiber

In standard single-mode fiber, a major part of light signal travels in the core while a small amount of light travels in the cladding. Optical fiber with lower group index of refraction provides an advantage in low latency applications. It is useful to use a parameter “effective group index of refraction (n_{eff}) instead of “index of refraction (n)” which only defines the refractive index of core or cladding of single mode fiber. The n_{eff} parameter is a weighted average of all the indices of refraction encountered by light as it travels within the fiber, and therefore it represents the actual behavior of light within a given fiber. The impact of profile shape on n_{eff} by comparing its values for several Corning single mode fiber (SMF) products with different refractive index profiles is illustrated in Fig. 2.

![Figure 2. Effective group index of refraction impact of various commercially available Corning single mode fiber types.](image)

It is known that speed of light in vacuum is 299792.458 km/s. Assuming ideal propagation at the speed of light in vacuum, an unavoidable latency value can be calculated as following in Equation (1):

\[
\text{Latency} = \frac{d}{c} \times 10^9 \times \frac{1}{10^6}
\]

where d is the distance in meter and c is the speed of light in vacuum.
However, due to the fiber’s refractive index light travels more slowly in optical fiber than in vacuum. In standard single mode fiber defined by ITU-T G.652 recommendation the effective group index of refraction (n$_{eff}$), for example, can be equal to 1.4676 for transmission on 1310 nm and 1.4682 for transmission on 1550 nm wavelength.$^{18}$ By knowing n$_{eff}$ we can express the speed of light in selected optical fiber at 1310 and 1550 nm wavelengths, see Equations (2) and (3):

$$V_{1310nm} = \frac{c}{n_{eff,1310nm}} = \frac{299792.458 \text{ km/s}}{1.4676} = 204273.956 \text{ km/s}$$

$$V_{1550nm} = \frac{c}{n_{eff,1550nm}} = \frac{299792.458 \text{ km/s}}{1.4682} = 204190.477 \text{ km/s}$$

By knowing speed of light in optical fiber at different wavelengths (see Equation (2) and (3) ) optical delay which is caused by 1 km long optical fiber can be calculated as following:

$$\frac{1310nm}{V_{1310nm}} = \frac{1 \text{ km}}{204273.956 \text{ km/s}} = 4.895 \text{ s}$$

$$\frac{1550nm}{V_{1550nm}} = \frac{1 \text{ km}}{204190.477 \text{ km/s}} = 4.897 \text{ s}$$

As one can see from Equations (4) and (5), propagation delay of optical signal is affected not only by the fiber type with certain n$_{eff}$, but also with the wavelength which is used for data transmission over fiber optical network. It is seen that optical signal delay values in single mode optical fiber is about $4.9 \text{ s}$. This value is the practically lower limit of latency achievable for 1 km of fiber in length if it were possible to remove all other sources of latency caused by other elements and data processing overhead.$^{7}$

Photonic crystal fibers (PCFs) can have very low effective refractive index, and can propagate light much faster than in SMFs.$^{14}$ For example, hollow core fiber (HCF) may provide up to 31% reduced latency relative to traditional fiber optics.$^{19,20}$ But there is a problem that attenuation in HCF fibers is much higher compared to already implemented standard single mode fibers (for SMF α=0.2 dB/km but for HCF α=3.3 dB/km at 1550 nm).$^{21}$ However, it is reported even 1.2 dB/km attenuation obtained in hollow-core photonic crystal fiber.$^{22}$

### 2.2 Chromatic dispersion compensation

Chromatic dispersion (CD) occurs because different wavelengths of light travel at different speeds in optical fiber. CD can be compensated by dispersion compensation module (DCM) where dispersion compensating fiber (DCF) or fiber Bragg grating (FBG) is employed.$^{23,24}$

A typical long reach metro access fiber optical network will require DCF approximately 15 to 25% of the overall fiber length. It means that use of DCF fiber adds about 15 to 25% to the latency of the fiber.$^{7,8}$ For example, 100 km long optical metro network where standard single mode fiber (SMF) is used, can accumulate chromatic dispersion in value about 1800 ps/nm at 1550 nm wavelength.$^{18}$ For full CD compensation is needed about 22.5 km long DCF fiber spool with large negative dispersion value (typical value is -80 ps/nm/km).$^{25}$ If we assume that light propagation speed in DCF fiber is close to speed in SMF then total latency of 100 km long optical metro network with CD compensation using DCF DCM is about 0.6 ms.

Solution how to avoid need for chromatic dispersion compensation or reduce the length of necessary DCF fiber is to use optical fiber with lower CD coefficient. For example, non-zero dispersion shifted fibers (NZ-DSFs) were developed to simplify CD compensation while making a wide band of channels available. NZ-DSF fiber parameters are defined in ITU-T G.655 recommendation.$^{26}$ Today NZ-DSF fibers are optimized for regional and metropolitan high speed optical networks operating in the C- and L- optical bands. For C band it is defined that wavelength range is from 1530 to 1565 nm, but for L band it is from 1565 to 1625 nm.$^{27}$
For commercially available NZ-DSF fiber chromatic dispersion coefficient can be from 2.6 to 6.0 ps/nm/km in C-band and from 4.0 to 8.9 ps/nm/km in L-band. At 1550 nm region typical CD coefficient is about 4 ps/nm/km for this type of fiber. It can be seen that for G.655 NZ-DSF fiber CD coefficient is about four times lower than for standard G.652 SMF fiber.\textsuperscript{15,28} Since these fibers have lower dispersion than conventional single mode, simpler modules are used that add only up to 5% to the transmission time for NZ-DSF.\textsuperscript{7} This enables a lower latency than using SMF fiber for transmission. Another solution how to minimize need for extra CD compensation or reduce it to the necessary minimum is dispersion shifted fiber (DSF) which is specified in ITU-T G.653 recommendation. This fiber is optimized for use in 1550 nm region and has no chromatic dispersion at 1550 nm wavelength. Although, it is limited to single-wavelength operation due to non-linear four wave mixing (FWM), which causes optical signal distortions.\textsuperscript{29}

If CD is unavoidable another technology for compensation of accumulated CD is a deployment of fiber Bragg gratings (FBG). DCM with FBG can compensate several hundred kilometers of CD without any significant latency penalty and effectively remove all the additional latency that DCF-based networks add.\textsuperscript{7} In other words, a lot of valuable microseconds can be gained by migrating from DCF DCM to FBG DCM technology in optical metro network.\textsuperscript{30} Typical fiber length in an FBG used for dispersion compensation is about 10 cm. Therefore, normally FBG based DCM can introduce from 5 to 50 ns delay in fiber optical transmission line.\textsuperscript{15,31}

One of solutions how to avoid implementation of DCF DCM which introduces addition delay is coherent detection where complex transmission formats such as quadrature phase-shift keying (QPSK) can be used. However, it must be noticed that it can be a poor choice from a latency perspective because of the added digital signal processing (DSP) time it require. This additional introduced delay can be up to 1 \textmu s.\textsuperscript{13,20}

### 2.3 Optical amplifiers

Another key optical component which adds additional time delay to optical transmission line is optical amplifier. Erbium doped fiber amplifiers (EDFA) is widely used in fiber optical access and long haul networks. EDFA can amplify signals over a band of almost 30 to 35 nm extending from 1530 to 1565 nm, which is known as the C-band fiber amplifier, and from 1565 to 1605 nm, which is known as the L-band EDFA.\textsuperscript{32} The great advantage of EDFAs is that they are capable of amplifying many WDM channels simultaneously and there is no need to amplify each individual channel separately. EDFAs also remove the requirement for optical-electrical-optical (OEO) conversion, which is highly beneficial from a low-latency perspective. However it must be taken into account that EDFA contains few meters of erbium-doped optical fiber (Er\textsuperscript{3+}) which adds extra latency, although this latency amount is small compared with other latency contributors. Typical EDFA amplifier contains up to 30 m long erbium doped fiber. These 30 m of additional fiber add 147 ns (about 0.15 \textmu s) time delay.\textsuperscript{7,15,33}

Solution how to avoid or reduce extra latency if amplification is necessary is use of Raman amplifier instead of EDFA or together (in tandem) with EDFA. This combination provides maximal signal amplification with minimal latency. Raman amplifiers use a different optical characteristic to amplify the optical signal.\textsuperscript{7,9,15} Raman amplification is realized by using stimulated Raman scattering. The Raman gain spectrum is rather broad, and the peak of the gain is centered about 13 THz (100 nm in wavelength) below the frequency of the pump signal used. Pumping a fiber using a high-power pump laser, we can provide gain to other signals, with a peak gain obtained 13 THz below the pump frequency. For example, using pumps around 1460–1480 nm wavelength provides Raman gain in the 1550–1600 nm window, which partly cover C and L bands. Accordingly, we can use the Raman effect to provide gain at any wavelength we want to amplify. The main benefit regarding to latency is that Raman amplifier pump optical signal without adding fiber to the signal path, therefore we can assume that Raman amplifier adds no latency.\textsuperscript{9,32,33}

### 2.4 Transponders and opto-electrical conversion

Any transmission line components which are performing opto-electrical conversion increase total latency. One of key elements used in opto-electrical conversion are transponders and muxponders. Transponders convert incoming signal from the client to a signal suitable for transmission over the WDM link and an incoming signal from the WDM link to a suitable signal toward the client.\textsuperscript{32} Muxponder basically do the same as transponder except that it has additional option to multiplex lower rate signals into a higher rate carrier (e.g. 10 Gbit/s services up to 40 Gbit/s transport) within the system in such a way saving valuable wavelengths in the optical metro network.\textsuperscript{34}

The latency of both transponders and muxponders varies depending on design, functionality, and other parameters. Muxponders typically operate in the 5 to 10 \textmu s range per unit. The more complex transponders include additional functionality such as in-band management channels. This complexity forces the unit design and latency to be very
similar to a muxponder, in the 5 to 10 s range. If additional FEC is used in these elements then latency value can be higher. Several telecommunications equipment vendors offer simpler and lower-cost transponders that do not have FEC or in-band management channels or these options are improved in a way to lower device delay. These modules can operate at much lower latencies, from 4 ns to 30 ns. Some vendors also claim that their transponders operate with 2 ns latency which is equivalent to adding about a half meter of SMF to fiber optical path.

2.5 Optical signal regeneration

For low latency optical metro networks it is very important to avoid any regeneration and focus on keeping the signal in the optical domain once it is entered the fiber. An optical-electronic-optical (OEO) conversion takes about 100 s, depending on how much processing is required in the electrical domain. Ideally a carrier would like to avoid use of FEC or full 3R (reaplication, reshaping, retiming) regeneration. 3R regeneration needs OEO conversion which adds unnecessary time delay. Need for optical signal regeneration is determined by transmission data rate involved, whether dispersion compensation or amplification is required, and how many nodes the signal must pass through along the fiber optical path.

2.6 Forward error correction and digital signal processing

It is necessary to minimize the amount of electrical processing at both ends of fiber optical connection. FEC, if used (for example, in transponders) will increase the latency due to the extra processing time. This approximate latency value can be from 15 to 150 s based on the algorithm used, the amount of overhead, coding gain, processing time and other parameters.

Digital signal processing (DSP) can be used to deal with chromatic dispersion (CD), polarization mode dispersion (PMD) and remove critical optical impairments. But it must be taken into account that DSP adds extra latency to the path. It has been mentioned before that this additional introduced delay can be up to 1 s.

2.7 Latency regarding OSI Levels

Latency is not added only by the physical medium but also because of data processing implemented in electronic part of fiber optical metro network (basically transmitter and receiver). All modern networks are based upon the Open System Interconnection (OSI) reference model which consists of a 7 layer protocol stack, see Fig. 3.

![Diagram of OSI Reference Model](image)

Figure 3. OSI reference model illustrating (a) total latency increase over each layer and (b) data way passing through all protocol layers in transmitter and receiver.

The upper layers of the OSI model (layers 5 to 7) describe processes that happen within the applications running on the computer. These applications are special software, web browsers, email programs, etc. The lower layers (layers 1 to 4) are where information to and from applications are turned into data for transport on a network, and it is mostly hardware implemented. This is where data encapsulation occurs and basic networking data element – the IP datagram or “packet” is built and ready for transmission over fiber optical network. As one can see in Fig. 3, the physical transport of information between applications occurs at the bottom of the OSI stack, in such a way forcing all data to have to tunnel...
down all seven layers for transport, and then back up the stack again after transport. Each of these layer transitions adds some amount of latency.

Layers 5-7 are where the application, presentation, and session layers are located. Information located at Layers 5 to 7 is referred to as data. Latency amount at these layers can be considered inversely proportional to computing power. Layer 4 is referred to as the transport layer of the network. It must be taken into account that no actual physical transport occurs at this layer. Information in transport layer is packaged into “segments”. Layer 4 serves as the doorkeeper for the applications that reside in layers above and it is substantial contributor to latency. It performs a number of functions including sequencing the packets into their proper position, controlling data flow, resend packets if necessary, etc. It must be mentioned, that there are connectionless and connection-oriented transport layer protocols. A connectionless protocol simply pushes data packets to the end destination without any special control and is often used for real-time communications such as voice or interactive video. Example of this type of protocols is User Datagram Protocol (UDP). Meanwhile, connection-oriented transport layer protocols are more complex because they rely on the establishment of the connection which requires handshakes and interaction between transmitter and receiver. One of them is Transmission Control Protocol (TCP) which is able to provide error free sequenced delivery of packets. It measures also the link performance - available bandwidth, delay and error rate.

Layer 3 is network layer where logical (Internet Protocol or IP) addressing and switching of packets is realized. Information at this layer is packaged into “packets”. In Fig. 4 is shown minimal time to transmit a packet with different size and data rate over network interface. This time in some sources is called serialization delay or network interface delay. It describes how much time is needed for conversion of stored data bytes into serial bit stream to be transmitted over fiber optical transmission line.

$$\text{Network interface delay} = \frac{\text{packet size (bits)}}{\text{data rate (bits/second)}} \tag{6}$$

Serialization or network interface delay can represent a significant delay on links that operate at lower data rates, but in most cases it is lower than delay introduced from other latency sources like fiber or OEO conversion.

Fig. 4 shows minimal time to transmit packet with different size (64 and 512 bytes) and data rates like 155 Mbit/s, 622 Mbit/s, 1 Gbit/s, 2.5 Gbit/s, 10 Gbit/s, 40 Gbit/s, 100 Gbit/s. For small packets this transmission or serialization time is significantly smaller than for large packets. For example, if data rate 10 Gbit/s is used, then network interface delay for 64 byte packet is 51.2 ns and for 512 byte packet 409.6 ns respectively. For 2.5 Gbit/s data rate and 64 byte packet this delay is 204.8 ns, but for 512 byte packet it is 1.638 s. Consequently, the larger is packet we want to transmit the more time we need for processing it with the same bit rate.

As mentioned before, latency depends on the network configuration and optical network path length. For example, assume that we want to transmit 1024 byte packet. By taking into account such latency sources like network interface delay and propagation delay in optical fiber, we can compare link with 1.25 Gbit/s bit rate against 10 Gbit/s link.
In Fig. 5(a) it is shown that upgrading from 1.25 Gbit/s to 10 Gbit/s provides 50% latency reduction over 1 km optical path. If optical path is extended up to 10 km then migration from 1.25 Gbit/s to 10 Gbit/s provides reduction 10% of total latency, see Fig. 5(b). But for 40 km optical path (Fig. 5(c)) reduction is 2.8% and for 80 km optical path (Fig. 5(d)) 1.4%, respectively.

![Figure 5. Total latency comparison of 1.25 Gbit/s and 10 Gbit/s optical metro links over (a) 1 km, (b) 10 km, (c) 40 km, and (d) 80 km optical path lengths.](image)

It can be concluded that there are trade-offs between migration to higher speed optical link and length of optical path. For shorter optical lines network interface delay has greater impact on total latency than for longer optical lines. It is because latency induced by long fiber spans becomes comparatively higher. Also, it must be mentioned, that reduction of packet length can significantly reduce network interface delay.

Layer 2 contains the data link layer where physical MAC addressing and switching occurs. Information at this layer is packaged into “frames”. Assuming a Layer 2 switch is undersubscribed, meaning the incoming frames sum up to less than the switching bandwidth available, then the only sources of latency will be framing-up to any line code present (e.g. 8b/10b) and buffering. The latency of buffering will depend upon the type used, either store-and-forward or cut-through. Therefore, the latency incurred will be a function of the size of the frame being buffered, as the entire frame must be buffered before being sent. The longer the frame, the longer you must wait before it can be sent.\(^4\)

Layer 1 is the lowest layer where the actual physical transport of information occurs. Information at Layer 1 can be simply called “bits”. This layer contains one of the largest contributors to latency – signal propagation delay through the fiber optical path. Ideally, bits containing information (e.g. trade command) should run down the OSI model stack at the beginning of transmission and not leave Layer 1 until it reaches receiver. It means that any OEO conversion must be avoided to keep latency as low as possible.\(^5\)

In table below we summarized the typical latency values induced by different line components in optical metro network we found during our research.

<table>
<thead>
<tr>
<th>Line component</th>
<th>Typical latency value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single mode fiber (SMF)</td>
<td>4.9 s per 1 km</td>
</tr>
<tr>
<td>DCF DCM</td>
<td>&lt; 25 % of ITU-T G.652 SMF fiber’s latency</td>
</tr>
<tr>
<td>FBG DCM</td>
<td>&lt; 5 % of ITU-T G.655 NZ-DSF fiber’s latency</td>
</tr>
<tr>
<td>Digital signal processing (DSP)</td>
<td>5 to 50 ns</td>
</tr>
<tr>
<td>Forward Error Correction (FEC)</td>
<td>&lt; 1 s</td>
</tr>
<tr>
<td>Optical EDFA amplifier</td>
<td>15 to 150 s</td>
</tr>
<tr>
<td>Optical signal regeneration (OEO conversion)</td>
<td>~ 0.15 s per unit</td>
</tr>
<tr>
<td>Transponders, muxponders</td>
<td>5 to 10 s</td>
</tr>
<tr>
<td></td>
<td>4 ns to 30 ns (ultra low latency transponders)</td>
</tr>
<tr>
<td>Optical signal regeneration (OEO conversion)</td>
<td>~ 100 s</td>
</tr>
</tbody>
</table>
3. OPTIMIZATION OF OPTICAL METRO NETWORK

In this section we present optimized model of 160 km long optical metro network operating at 10 Gbit/s bitrate. The aim of this section is to show how much optical metro network can be optimized in terms of latency by replacing conventional latency inducing optical and electrical components to low-latency components. In Fig. 6 we propose two optical transmission networks – conventional and latency optimized, see Fig. 6(a) and Fig. 6(b).

First optical metro network (Fig. 6(a)) consists of two transponders, DCF DCM for CD pre-compensation, two EDFA amplifiers to boost optical signal, and two 80 km long ITU-T G.652 SMF fiber spans.

Pre-compensation configuration of accumulated chromatic dispersion was chosen because our researches proved it more effective than post-compensation method.\textsuperscript{23,24} Fiber optical line is chosen 160 km in length because typically fiber optical metro networks are up to 200 km long.\textsuperscript{2}

Second network scheme is latency optimized (see Fig. 6(b)), where we replaced conventional transponders by ultra-low latency transponders, DCF DCM replaced by FBG DCM and EDFA amplifiers are replaced by Raman amplifiers.

For total latency calculations of both optical systems we assume that 64 byte packet (typical size for market data messaging systems) which adds 51.2 ns network interface delay is transmitted. Here we used typical latency parameters described in section 2 of this work and compared results in Table 3.

<table>
<thead>
<tr>
<th>Line component</th>
<th>Conventional Metro network</th>
<th>Latency optimized Metro network</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 x 80 km ITU-T G.652 SMF fiber spans</td>
<td>4.9 s x 160 km = 784 s</td>
<td>4.9 s x 160 = 784 s</td>
</tr>
<tr>
<td>1 CD compensation module (DCM)</td>
<td>DCF DCM: 25% of 784 s = 196 s</td>
<td>FBG DCM: 50 ns</td>
</tr>
<tr>
<td>2 Optical amplifiers</td>
<td>EDFA: 2 x 0.15 s = 0.3 s</td>
<td>RAMAN adds no delay</td>
</tr>
<tr>
<td>2 Transponders</td>
<td>2 x 10 s = 20 s</td>
<td>2 x 4 ns = 8 ns</td>
</tr>
<tr>
<td>2 Network interface delays</td>
<td>2 x 51.2 ns = 102.4 ns</td>
<td>2 x 51.2 ns = 102.4 ns</td>
</tr>
<tr>
<td>Total latency value</td>
<td>1 ms</td>
<td>0.784 ms</td>
</tr>
</tbody>
</table>

As one can see from Table 3, total latency amount is reduced by 21.6% or 216.24 s. In this case the main benefit comes from optimization of chromatic dispersion compensation scheme from DCF DCM to FBG DCM and replacement of conventional transponders to low latency transponders.
4. CONCLUSIONS

We report on causes of latency in fiber optical metro networks and solutions how to minimize it. Latency is a critical parameter in a wide set of applications like financial transactions, telemedicine, cloud services and other real-time applications which requires optical transmission line with the smallest available time delay. It was shown that latency can be greatly reduced by replacing conventional network components by low-latency components and by optimizing optical network path trying to keep it short as possible. Our calculations showed that latency of 160 km long optical metro network can be reduced up to 21.6% by carefully choosing and replacing existing line components.

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REFERENCES

wdmsummit.rlc.cz/pdf/07_Niemyjski_Application_focus_-_Datacenter_interconnect.pdf