Low latency data transmission using wireless and wired communications

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Abstract— **This paper describes impact of wave propagation speed on latency in data transmission systems. The wave propagation in conventional optical fibers is slower than in vacuum. Low earth orbit satellites would provide low latency data transfer. Fibers with low effective refractive indices such as photonic crystal fibers would be media for low latency transmission.**

Keywords-component; fiber; latency; propagation speed

I. INTRODUCTION

High capacity transmission is indispensable to mitigate huge data communication demands [1, 2]. In addition, latency is a very important figure to describe performance of transmission systems for particular applications, such as data transmission for earthquake early warning, transaction for financial or banking businesses [3, 4], interactive services such as online games [5]. Latency consists of delay due to signal processing at nodes, transmitters and receivers, and of signal propagation delay due to finite speed of electromagnetic waves. Signal processing delay can be reduced by using parallel processing based on large scale integration CMOS technologies. However, propagation delay has an absolute limit because any electromagnetic waves should not be faster than light in vacuum. Thus, the lower limit of the latency in optical transmission systems using conventional single mode fibers (SMFs) depends on the speed of light in SMFs which is 67% of the speed of light in vacuum c. In free space optic wireless (FSO) systems, signals can propagate with the speed c, so that the latency would be smaller than in optical fiber communication (OFC) systems. For example, optical wireless systems using low earth orbit (LEO) satellites would transmit data faster than optical submarine cable systems, when the transmission distance is longer than a few thousand kilometers. Photonic crystal fibers (PCFs) can have very low effective refractive index, and can propagate light much faster than in SMFs. Thus, cables with PCFs also can reduce the latency in transmission. In this paper, we will discuss the latency and capacity of wireless and wired optical communication systems. We will also describe possible applications of ultra low latency transmission.

II. HIGH-SPEED DATA TRANSMISSION

In optical communication systems, high-speed modulation and demodulation with advanced modulation formats play important roles to achieve high bit rate of each optical channel. For example, dual polarization 16-level quadrature amplitude modulation (QAM) can provide 100 Gb/s, when the modulation speed is 12.5 Gbaud [1]. An optical fiber can carry many channels by using wavelength domain multiplexing (WDM), and space domain multiplexing (SDM). High-speed optical fiber transmission of which bit rate is over 300 Tb/s is recently demonstrated by using a multi-core fiber [2]. In this context, "high speed" means high transmission capacity. On the other hand, high-speed signal propagation can reduce time delay of response in transmission systems. The delay is called latency. Figure 1 shows time domain data packet envelopes at a transmitter and at a receiver. The packet length in time domain is given by $t_D = D/R$, where D [bit] is the size of the data and R is the bit rate. The latency t_L consists of delay due to signal processing at nodes, transmitters and receivers, and of signal propagation delay in fibers. The propagation delay due to finite speed of electromagnetic wave gives the absolute lower limit of latency in data transport systems. Thus, t_L should be larger than L/v_i, where L is propagation length and v_i is signal propagation speed. As described above, normally, "high speed transmission" does not mean high speed propagation of signals in transmission media. The total duration of data transfer given by $T = t_D + t_L$ is decreasing function of R and v_i. When t_D is dominant in the duration, T can be largely reduced by increasing the transmission capacity (bit rate) R. This is the reason why high speed in transmission means high capacity.
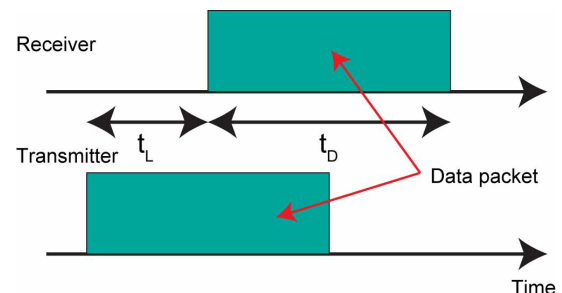

Figure 1. Time domain profiles of signal envepoles at at recievers and transmitters.

Optical fiber cables are commonly used for long-haul high-capacity transmission. For example, Unity is one of high capacity transoceanic submarine cables, connecting Chikura in Japan and Los Angeles in USA. The total transmission capacity is 4.8 Tb/s. The distance between Chikura and Los Angeles is 9620 km. Thus, if we assume that light propagation speed in fibers is 67% of c, the propagation delay should be 48.1 ms. The latency t_L should be larger than this delay. If we focus just on bit rate, huge capacity data transmission can be achieved by physical transportation of storage media. As an example, here, we estimate digital data transmission capacity of an air cargo plane. We consider that data in memory cards would be carried by a B747-400 air plane flying between Tokyo Narita (NRT) and Los Angeles (LAX). Narita is very close to Chikira in the Tokyo metropolitan area. Time duration was assumed to be 24 hours including custom and other required processes at airports. The maximum payload of the airplane is 94 tons in weight. In addition, the volume of the payload should be smaller than 80 m^3. If the weight density of the payload is larger than 1.175 g/cm^3, the payload would be limited by weight. Here, we assumed to use 32 GB micro SD cards whose weight density is 2.42 g/cm^3. The weight of one memory card is 0.4 g, so that the airplane can carry $2.35 \times 10^8 = (92 \times 10^3) / (0.4 \times 10^{-3})$ memory cards, which corresponds to 7.5 EB. If overhead for packing is 40%, the total transmission capacity would be 500 Tb/s. The transmission capacity is much larger than in the submarine cable, Unity. However, the duration of air cargo is 24 hours, even if the data size is much smaller than 7.5 EB. If the definition of "high speed" is high capacity in transmission, the data transfer with air cargo should be high speed. Of course, it is not feasible for typical applications of networks, such as teleconference, email, etc., because airplanes are much slower than lightwaves in fibers. Figure 2 shows time duration of data transmission using the submarine cable (Unity) and the airplane (B747-400), where we neglected delay in repeaters, transmitters and receivers of the submarine cable systems. Obviously, the duration is much smaller in the cable than in the airplane, when the data size is not large. However, the duration in the cable has the lower limit of 48.1 ms. This is due to light wave propagation delay in fibers. When the data size is larger than 52 PB, the total time duration of the airplane would be smaller than in the cable. Thus, we may deduce that physical transportation of storage media would be competitive for distribution of huge data, such as high definition movies.

For comparison, we also roughly estimated energy consumption of the B747-400 and Unity. CO_2 emission of the airplane would be 350 tons for one way flight (average of westbound and eastbound between Narita and Los Angeles), while that of a typical submarine cable for 24 hours would be 0.27 tons for bidirectional transmission. The power consumption per b/s would be 23 times larger in air cargo than in submarine cable transmission. Thus, we can deduce that optical fiber communications is more energy-efficient than physical transportation by air cargo. However, power consumption of nodes would be dominant in network systems. This implies that the power consumption difference might be smaller.

In addition to transmission capacity (or throughput) R, the latency would be very important to describe digital data transmission systems, as we discussed in this section. Lightwave in optical fibers is fast enough for various applications, such as file transfer, email, etc. However, we should carefully design the latency in transmission systems for some particular applications. We will discuss speed of light in transmission media, and low latency transmission systems, in the following sections.
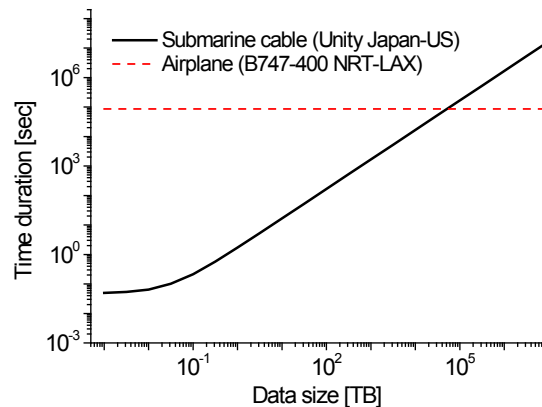

Figure 2. Time duration of tranceoceanic data transmission using a submarine cable and an air plane.

III. PROPAGATION SPEED OF ELECTROMAGNETIC-WAVE

Propagation delay due to finite speed of electromagnetic wave gives the absolute lower limit of latency in data transport systems. As well known, the propagation speed of information over electromagnetic-wave (v_i) should be smaller than the speed of light c. Group velocity v_g describes propagation speed of wave packets and should be smaller than c in many cases, while phase velocity v_p can be larger than c [7]. The group velocity v_g shows the propagation speed of information v_i in common data transmission systems. However, in dispersive transmission media with some particular conditions, v_g can be larger than c [8]. Thus, t_L can be smaller than L/c or zero. As shown in Figure 3, when t_L is smaller than zero, peak of output signal waveform would precede that of input signal waveform. In such cases, the causality does not have direct connection to v_g, so that v_i is not equal to v_g. Speed of pulse front is called front velocity v_f, which is always smaller than c and is connected the causality. In other words, v_i should be smaller than v_f. However, differences in these four velocities, v_p, v_g, v_f and v_i, are not so large in transmission media commonly used for telecommunications. In optical fibers, v_i, can be approximately described by c/n, where n is effective refractive index. Thus, we will focus on n in the following sections. Real part of n should be larger than one, when $v_g < c$.

In SMFs, n is about 1.5, but depends on material and waveguide structure. As described in Ref. [4], the refractive indexes of commercially available SMFs have 0.5% differences. If we use the lowest index fiber in the reference instead of a conventional SMF, for transoceanic cables, the delay difference is not negligible. In the 9620-km submarine

cable system, the difference would be 260 μs, which is corresponding to 26 Mbit of 100-Gb/s bit streams. The delay difference would have large impact in some particular applications, such as high-frequency trading. Recently, many types of optical fibers using fine structures have been reported to improve dispersion characteristic, transmission loss for wideband signals, etc. PCFs have periodic structures in cladding, and can guide lightwaves along air cores. Signal propagation speed (v_i) in PCFs can be close to c. Thus, the latency due to lightwave propagation can be drastically reduced by using PCFs for data transmission. However, we still have open issues on fabrication of long PCFs and on reduction of bending losses, etc.

In free space transmission including FSO and radio wave wireless communications, v_i is approximately equal to c, because the difference between n of air and that of vacuum is almost zero. In general, the total transmission capacity of OFC is larger than FSO, because of propagation loss and fluctuation in the air. OFC is also suitable for long-haul transmission, where optical amplifier can regenerate optical signals without using optical-to-electric or electric-to-optical conversion. On the other hand, the latency of FSO would be much smaller than in OFC, because v_i in the air is 1.5 times larger than in SMFs.
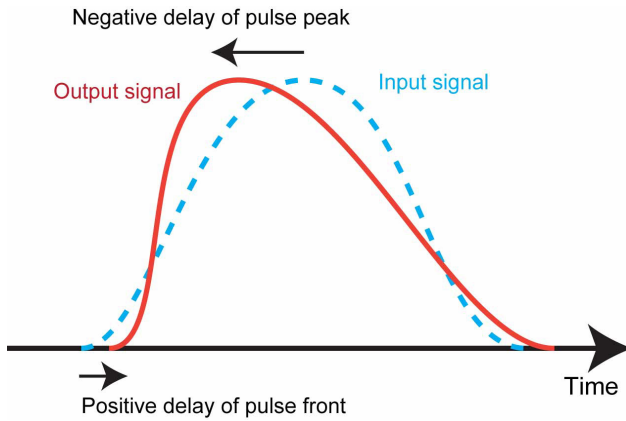

Figure 3. Time domain profile of input and output singals in dispersive medium with negative group delay.

IV. LATENCY IN SATELLITE COMMUNICATION SYSTEM

As described above, the latency in FSO systems would be small than in OFC systems. Terrestrial FSO would reduce the latency due to propagation delay, because the length of links would be similar to or shorter than that of OFC. Most of terrestrial FSO systems are designed for last-mile connection. In 4-km transmission, the latency of FSO is 13 μs, while that of OFC is 21 μs. The difference would have impact on some particular applications, such as high-frequency trading. Satellite communication would be feasible for long-haul transmission. However, geostationary earth orbit (GEO) satellite communication is not suitable for latency sensitive applications, because the latency of transmission via GEO satellites is much larger than that of OFC using submarine cables. Here, we consider the latency due to lightwave propagation in LEO satellite systems. The latency consists of

delays in ground-to-satellite, inter-satellite and satellite-to-ground links. As shown in Ref [9], the delays of ground-to-satellite link $t_{L(uplink)}$ and that of satellite-to-ground link $t_{L(downlink)}$ can be approximately given by

$$t_{L(uplink)} \approx t_{L(downlink)} \approx \frac{h}{c}, \qquad (1)$$

where h is the satellite altitude. As shown in Figure 4, we assume that lightwaves connecting the satellites are assumed to propagate along with a circular orbit whose radius is R_e+h, where R_e is the radius of the earth, for simplicity. The delay of inter-satellite links can be expressed by,

$$t_{L(crosslink)} \approx \frac{L}{c}\left(\frac{R_e+h}{R_e}\right). \qquad (2)$$

In actual LEO satellite communication systems, the propagation delay would be larger than this, because the lightwaves propagating between the satellites should have some walk-off from the circular orbit. If the number of the satellites and the transmission distance L are large enough, the walk-off would be small. The total propagation delay can be described by

$$t_{L(LEO)} = t_0 + \frac{h}{c}\left(2 + \frac{L}{R_e}\right), \qquad (3)$$

where t_0 ($=L/c$) is the absolute lower limit of propagation delay. The latency in an OFC system whose refractive index is n is

$$t_{L(OFC)} = t_0 + (n-1)\frac{L}{c}. \qquad (4)$$

When

$$n > h\left(\frac{2}{L} + \frac{1}{R_e}\right) + 1, \qquad (5)$$

$t_{L(LEO)}$ can be smaller than $t_{L(OFC)}$, and the signal sent via LEO satellites can precede the signal over fibers. Here, we define effective refractive index of LEO by

$$n_{LEO} = h\left(\frac{2}{L} + \frac{1}{R_e}\right) + 1. \qquad (6)$$

n_{LEO}^{-1} describes relative signal propagation speed in a LEO satellite system connecting two points on the ground. Figure 5 shows the effective refractive index n_{LEO} for various distances L. When the altitude is smaller than 1370km, n_{LEO} for 9620-km transmission is smaller than n (=1.5) of SMF. As shown in Figure 6, n_{LEO} asymptotically goes to $h/R_e + 1$. When $h = 600$km and $L = 20000$km, $t_{L(LEO)}$ is 77% of $t_{L(OFC)}$ ($n_{LEO} = 1.15$). This implies that LEO satellite systems may provide ultra low latency long-haul transmission. Figure 7 shows differences in delays $t_{L(LEO)}$ and $t_{L(OFC)}$, calculated by using the equations (3) and (4). The difference can be larger than 10ms, which is much larger than that of OFC with low refractive index fibers. As mentioned above, the optical link would have some additional

delay due to the walk-off from the circular orbit. We need more detailed discussion on satellite constellations to calculate the propagation delay accurately.
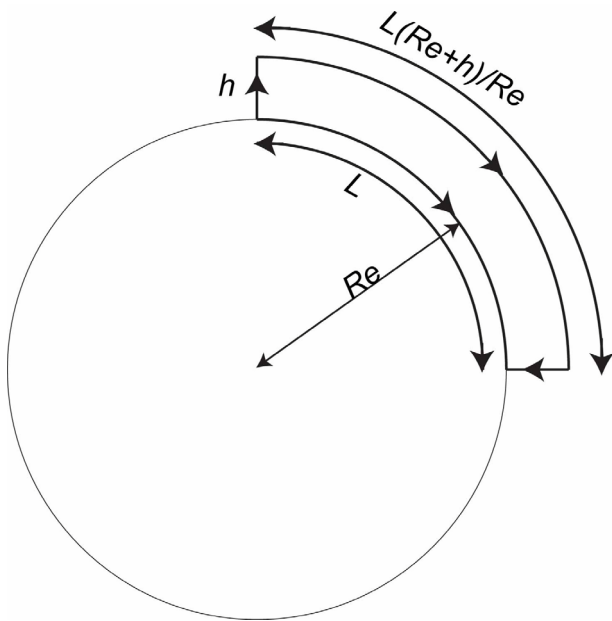

Figure 4. Schematic of lightwave propagation paths of LEO and OFC based transmission systems.
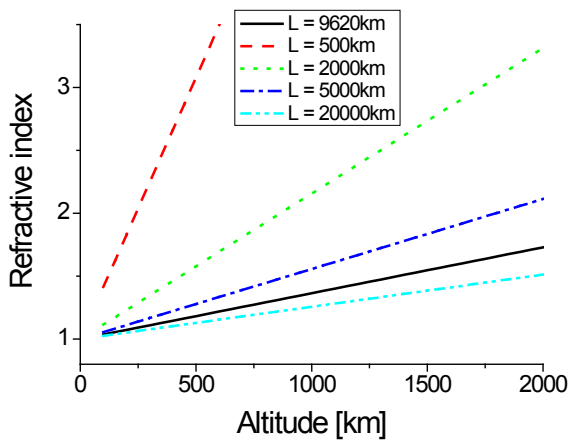

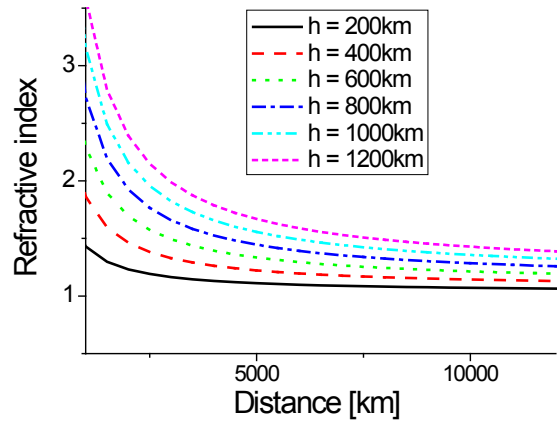Figure 5. Effective refractive index of LEO satellite systems for various altitudes.

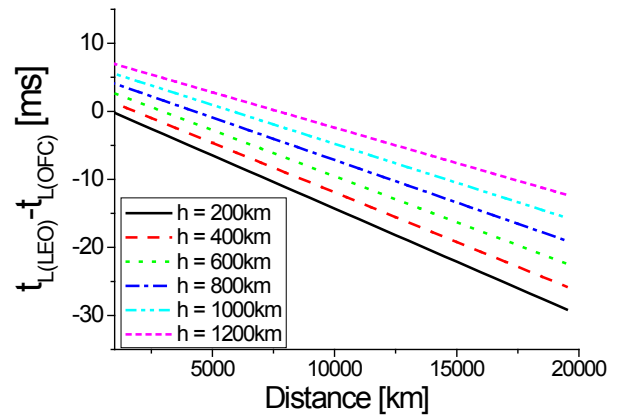Figure 6. Effective refractive index of LEO satellite systems for various altitudes.

Figure 7. Differences in delays of LEO and OFC based transmission.

V. DISCUSSIONS

Low latency transmission is required in particular applications, such as data transfer for high-frequency trading, online gaming. As we discussed, LEO satellite based transmission systems can reduce the latency. Radio-waves reflected by ionosphere also might provide high-speed signal propagation [10]. Wired transmission using PCFs also would be a candidate for low latency communications. The refractive index of PCFs can be close to one [11]. However, expected transmission capacity of LEO satellites, radio-waves or PCFs, would be much smaller than in OFC using WDM and SDM. Availability of FSO or radio-wave wireless systems would be an issue in mission-critical applications, such as high-speed transmission for financial or banking businesses. To pursue total capacity and latency, we may consider combination of different types of transmission media. For example, we can send some control signals to receiver side via LEO satellites, while data for normal transactions are sent by OFC. When we detect rapid change of market, we can cancel the data for

transaction already sent by OFC, because the control signal in the air can overpass the data in optical fiber cables.

ACKNOWLEDGMENT

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