Requirements for Radio-Wave Photonic Devices from the Viewpoint of Future Mobile Radio Systems

Shozo Komaki, *Senior Member, IEEE,* Katsutoshi Tsukamoto, and Minoru Okada

Abstract—**Air interfaces of mobile communication are spreading widely because of diversified service demands, technology trends, and radio propagation conditions. This paper proposes the Radio High-way Network, which universally supports any mobile services and any mobile radio air-interface. As one example of the network, we analyze the optical TDMA signals for radio and show some requirements for radio-wave photonic devices.**

I. Introduction

CELLULAR MOBILE radio communication systems are separated into two portions—the information transfer network portion and the radio link portion; both are connected by digital baseband signals in current systems. The future radio access portion should have seamless connection among the huge number of radio base stations. This is essential because cell numbers will continue to increase with advances in microcellular technology that enhance frequency reuse efficiency. Moreover, in future systems, the radio signal air-interface will rapidly change and diversify because multimedia personal communications require various signal speeds, network topology, and service frequency bands. As a result, mobile communication systems should have more global seamless access capability supporting all types of radio signal formats. The importance of universal networking for various types of radio signals will become more and more critical with multimedia micro cellular and pico cellular systems.

Recent developments in fiber-optics and cellular radio communications have been very rapid and many new communication systems have resulted, however these two technologies are growing in isolation. They can be combined synergistically to solve the above-mentioned problems and develop universal radio access networks.

Section II of this paper outlines the existing mobile radio systems in Japan to delineate the operation frequency of radio-wave photonic devices, and Section III introduces the state-of-the-art of Radio-wave Photonic and problems involved. Section IV proposes the radio High-way network based on radio-wave photonic technology as one way of realizing universal radio networks. Section V analyzes system considerations and performance. The analysis adopts the radio signal on optical TDMA method as one practical example of a Radio High-way Network. Section VI summarizes the requirements for the radio-wave photonic devices that will realize Photonic TDMA Radio High-way Networks.

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II. Mobile Radio Progress in Japan and Operating Frequencies

Japanese mobile radio topics are shown in Fig. 1. At the beginning of 1990, radio technology was being applied in the maritime and mobile communication fields. In the first part of the 1990's, HF frequency bands and noncellular technology were employed. In the mid 1990's, cellular technology was put into commercial use in an analog cellular radio system; the VHF or lower UHF frequency bands were used. At the present time, digital cellular radio systems are operating in the upper UHF bands, and the current movement is towards microcellular radio systems; the frequency bands have become higher and higher, from HF and VHF to UHF, and cell size has become smaller and smaller to satisfy the increase in subscriber number and capacity.

In the 2000's, it is assumed that multimedia personal communication, such as mobile computing and personal digital assistance, will predominate. Thus, higher frequency bands such as SHF and picocellular technology will have to be used commercially. The radio-wave photonic devices for mobile applications [1]–[16] will have to operate in the SHF or lower EHF frequency bands, such as microwave and millimeter wave bands up to 30 or 50 GHz.

III. State-of-the-Art Radio-Wave Photonic Devices and Problems

Some problems prevent us from realizing the radio-wave photonic link. One is the inter-modulation noise of the optical link, which is mainly caused by the third-order nonlinearity of the E/O converter, as shown in Fig. 2. The other problem is the fluctuation in received signal level due to wireless propagation conditions. In actual mobile communication systems, the

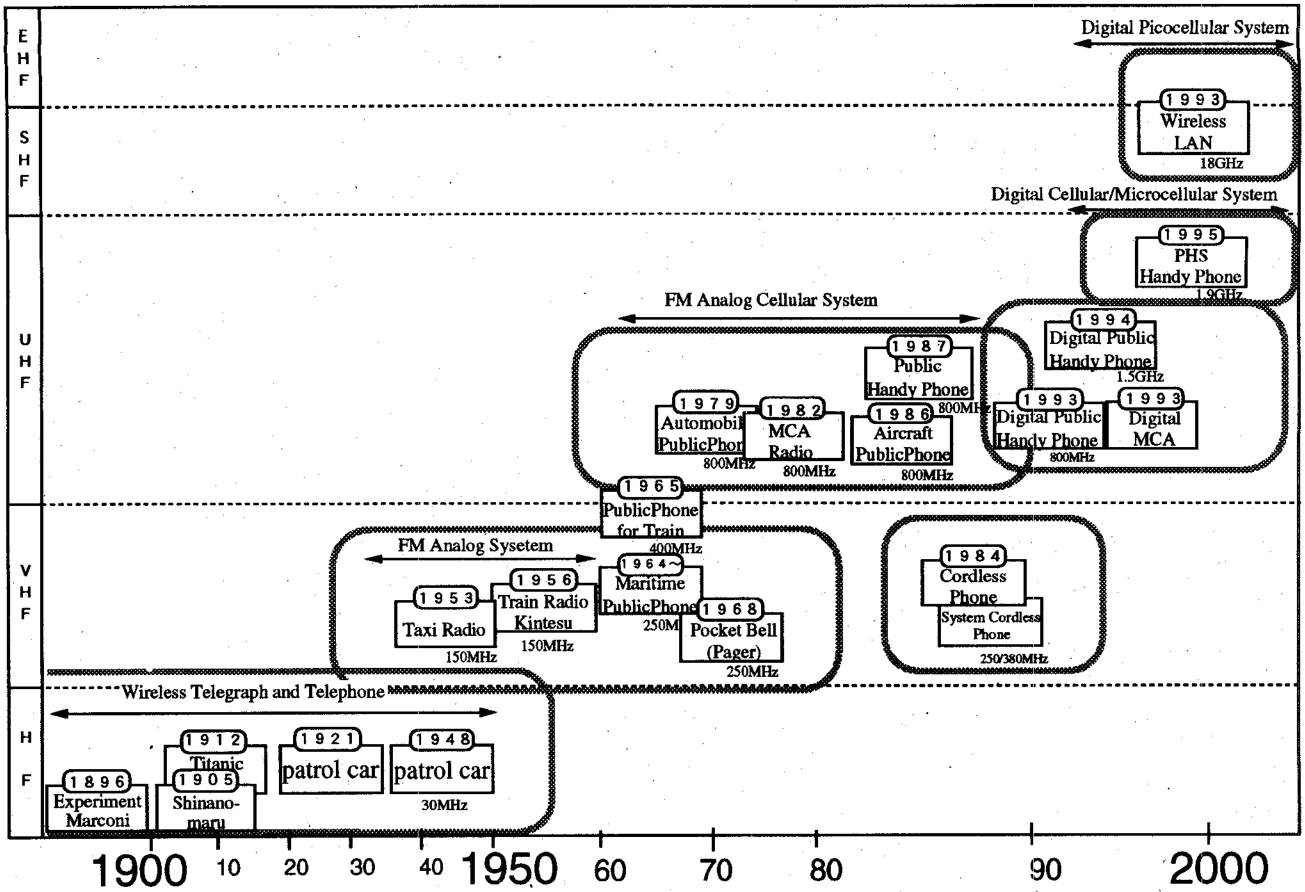

Fig. 1. Mobile radio in the 1990's.

distance between mobile stations and a base station are not the same for each mobile station and, moreover, multipath fading exists in the propagation path. Accordingly, the received signal levels of all mobile stations fluctuate widely at very high speed. In counteracting nonlinearity degradation, the received signal level difference due to multipath fading should be taken into consideration. In this paper, we assume that the signals received from the mobile stations have Rayleigh distributions with the same average power that are statistically independent. When the received signal level from the ith mobile station is denoted by r_i, the probability density function of r_i is as follows:

$$p(r_i) = r_i/\sigma^2 \exp\left(-r_i^2/2\sigma^2\right) \tag{1}$$

where, σ^2 is the average power. The received signal r is

$$r = \sum_i r_i \cos \omega_i t \tag{2}$$

where ω_i is the carrier frequency of the ith mobile station. The received signal is converted into an optical signal by a laser diode. The laser diode has nonlinear characteristics between the input diode current and the output optical power and this nonlinearity adds an undesired intermodulation signal to r_i. The optical signal is reconverted to a radio frequency signal by the photodetector. Signal to noise power ratio of the detected signal is shown by the following equation [8]:

$$C/(N+D) = \frac{\frac{1}{2}m^2 I_{\mathrm{ph}}^2}{\{\mathrm{RIN}\, I_{\mathrm{ph}}^2 + 2eI_{\mathrm{ph}} + \langle I_{\mathrm{th}}^2\rangle + \sigma_{\mathrm{IM}}^2\}\,\mathrm{BW}} \tag{3}$$

where m, I_{ph}, RIN, $e, \langle I_{\mathrm{th}}^2\rangle, \sigma_{\mathrm{IM}}^2$ and BW are optical modulation index, detected signal photo current, relative intensity noise, electron charge, equivalent input-noise-current variances, equivalent intermodulation spectrum density, and signal bandwidth, respectively. Output signal of the nonlinear device is denoted by the following equation:

$$P = P_o\left[1 + a_1 \sum_i r_i \cos\omega t + a_2\left(\sum_i r_i \cos\omega t\right)^2 + a_3\left(\sum_i r_i \cos\omega t\right)^3 + \cdots\right]. \tag{4}$$

Among the intermodulation components, the third intermodulation interferes most with the original signal, and the intermodulation noise is shown in the following equation when the radio signal consists of three tones:

$$\sigma_{\mathrm{IM}}^2\,\mathrm{BW} = \tfrac{1}{2}\left(\tfrac{3}{2}a_3 r_1 r_2 r_3\right)^2 I_{\mathrm{ph}} \tag{5}$$

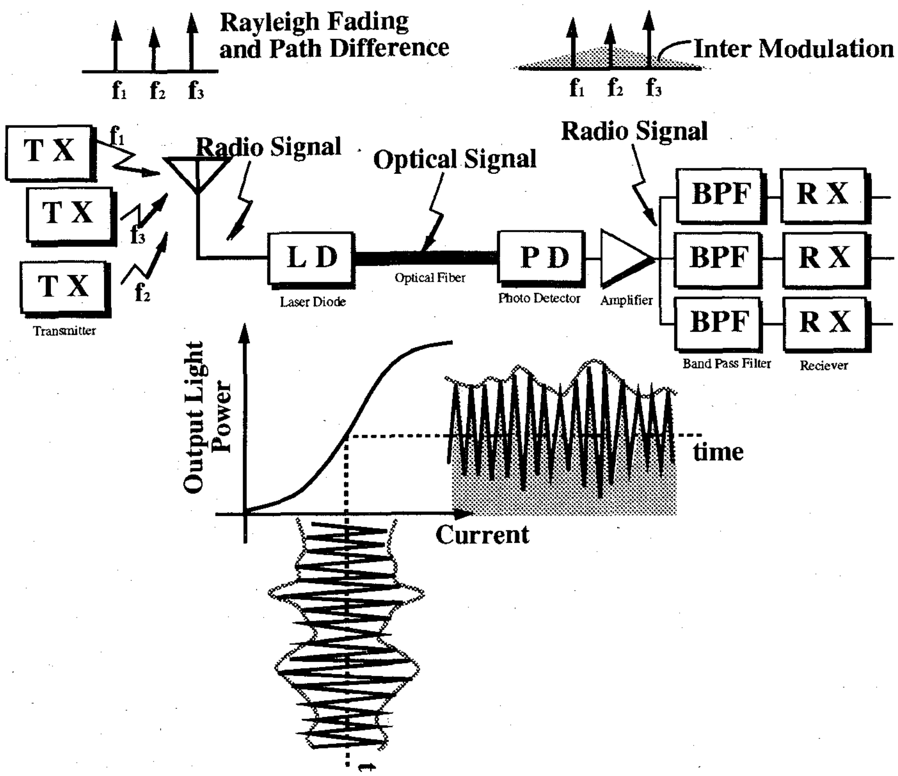

Fig. 2. Intermodulation of the FREx link.

where, the interfered signal is the center of the three tones, i.e. signal r_2. In this analysis, r_i is Rayleigh distributed as shown in (1), and the average C/N is calculated by the following equation:

$$\langle C/(N+D)\rangle = \int \cdots \int_0^\infty C/(N+D)p(r_1)p(r_2)\cdots \cdot p(r_m)\,dr_1\,dr_2\cdots dr_m. \quad (6)$$

Fig. 3 shows the calculated examples, and the results show that almost the same transmission performance can be realized even if fading is take into consideration. However, optic link nonlinearity limits the system performance, such as maximum operation number of carriers. This problem has been tackled, and various ideas have been proposed [14]–[16].

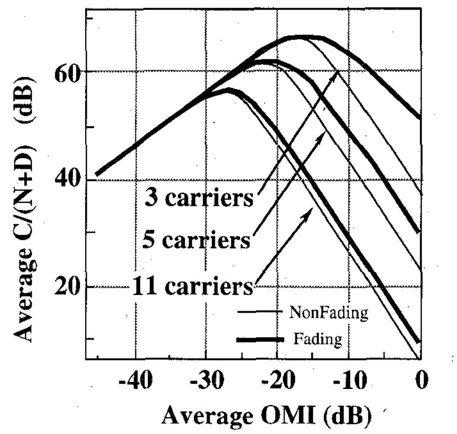

Fig. 3. Photonic link C/N considering fading effects.

Another problem occurs when several mobile base stations share one optical fiber to reduce construction cost and to enhance base station construction flexibility as shown in Fig. 4(a). In the figure, several mobile base stations are installed on one fiber with a bus connection. There are some problems with this configuration. One problem is that every mobile base station must use a photonic coupler and the theoretical coupling loss is 3 dB for every connection point. This is very large compared to the fiber loss and requires the use of photonic amplifiers. Another problem is beat noise among the base station laser diodes, as shown in Fig. 4(b). The photonic center frequency Δf and spectrum width $\Delta\nu$ of the laser diodes fluctuate. This generates beat noise in the detection of optical signals in the control center shown in Fig. 4(a). This beat noise limits the received RF signal Carrier to Noise power Ratio (CNR). One theoretical example is shown in Fig. 5. The figure shows that the received CNR decreases as the number of base stations increases and is not improved by increasing the optical power.

IV. Proposal of the Radio High-Way Network

In the conventional mobile radio system, radio signals transmitted from the mobile terminal are converted to baseband signal at the appropriate base stations, as shown in Fig. 6(a). The base stations are connected to digital backbone networks. The radio signal formats are usually different for different

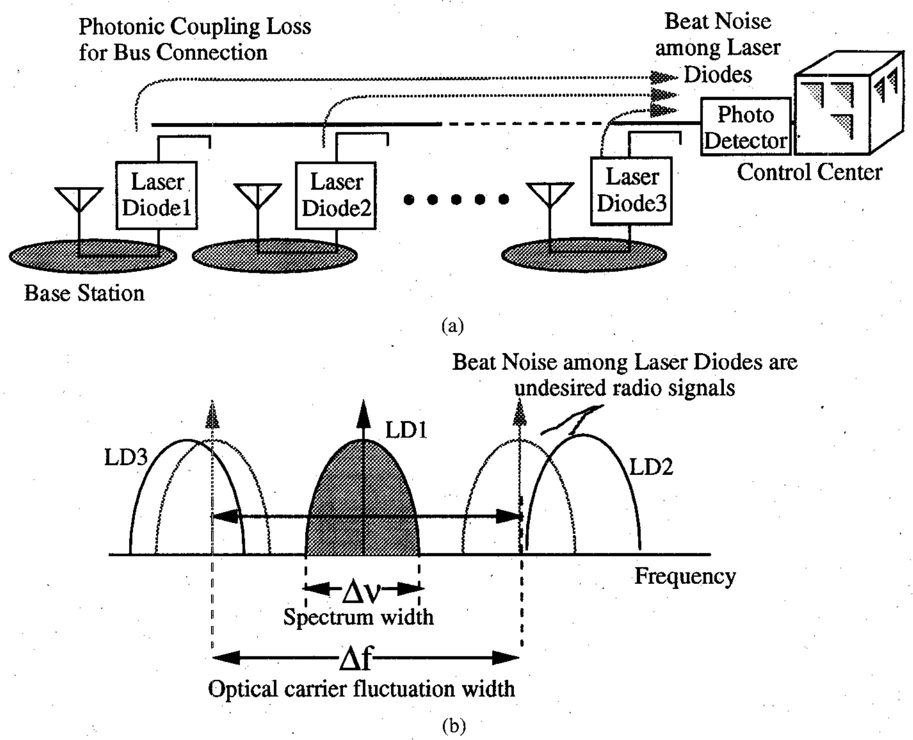

Fig. 4. Radio-wave photonic link with bus connection. (a) Configuration of bus-type optical network. (b) Mechanism of beat noise generation.

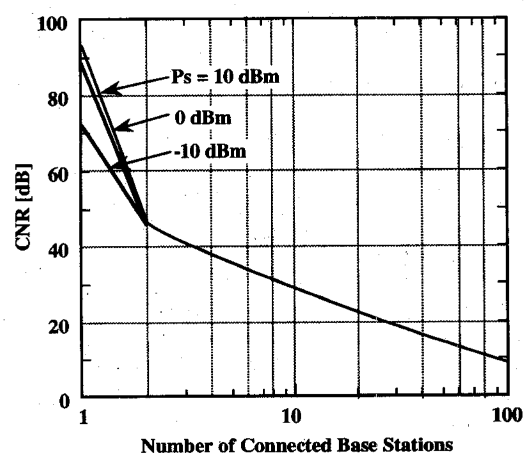

Fig. 5. Performance of radio-wave photonic link with bus connection.

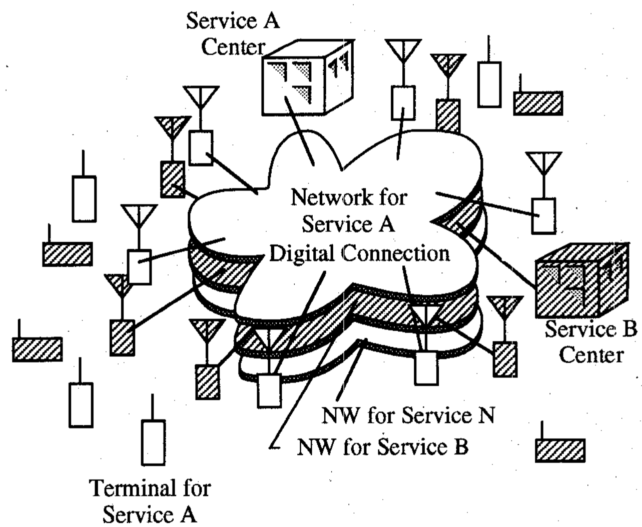

Fig. 6. Existing network configuration.

mobile services, shown by the black and white terminals. For these different services, different types of base stations are needed because of the air interface difference. Thus, the base stations and networks should be segregated into various services and operators.

To eliminate the excessive investment typical of conventional systems, we propose the concept of the Radio High-way Network. The concept is illustrated in Fig. 6(a).

The proposed system consists of optical links and optical routing nodes. The optical link is the radio wave photonic link, and optical routing nodes are optical switches. In the system, radio signals transmitted by the radio terminals are encapsulated into optical signal envelopes and transferred to the appropriate remote radio control station via several optical routing nodes. The received optical envelope is decapsulated to yield the radio signals. At intermediate optical routing nodes, the envelop is switched to the appropriate network node. Consequently, the system can open the radio free space of any cell to any remote control station and can switch the radio free space instantaneously according to the demands of the mobile users or service provider. We call this space the "Virtual Radio Free Space," and the system is named the "Radio High-way Network." This network can be universally used for any type of air interface because the virtual space links all users. A new service can be started by installing only one radio transceiver in a radio control station and existing radio base stations and

TABLE I
COMPARISON OF RADIO-WAVE PHOTONIC DEVICES

Devices or Parts	TDMA Type Radio Highway (Proposed)	FDMA Type Radio Highway (Coherent)
Laser Diodes	Normal LD (○)	High coherency (×)
Radio to Photonic Modulator	Normal E/O convertor (○)	Normal E/O convertor (○) or FM/PM modulator (×)
Bus Duplexer	High Speed Switch (○)	Photonic FDM Duplexer (×)
Network Switch	Time Switch (○)	Photonic Frequency Converter (×)
Receiver	Normal Photodiode & RF BPF (○)	Coherent Detector or Photonic BPF (×)

networks do not need to be replaced. The Radio High-way allows us to immediately start any new multimedia-personal service.

The Radio High-way Network is also applicable to indoor multimedia networks, such as data voice and video communications. It can support any radio LAN interface in the VHF, UHF, SHF or EHF bands and also realizes seamless connection capability from any room to any room, even if the rooms use different types of radio LAN systems. We call this "Radio WAN," instead of "Radio LAN," which offers digital baseband connection using backbone optical networks.

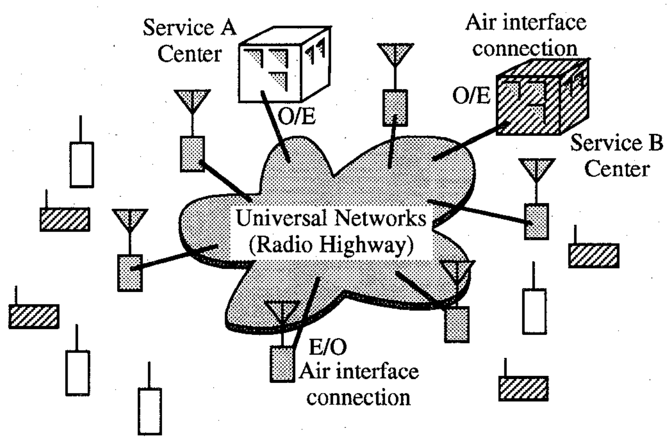

Fig. 7. Concept of the Radio High-way Network.

V. RADIO HIGH-WAY NETWORK REALIZED BY THE OPTICAL TDMA METHOD

In Section IV, we proposed only the concept of Radio Highway network and did not describe how can the Radio Highway was realized. This section describes tangible realization methods and some results of a performance analysis. The Radio High-way can be realized by many methods, such as FDMA, TDMA, SDMA, and CDMA [2]–[6]. Multiple access is performed both optically and/or in the radio stage. We think that TDMA in the optical stage suits the modern optic technology of high-speed digital communications. As the first step, we analyzed the Radio High-way as realized by the Photonic TDMA method. Fig. 7 illustrates details of the TDMA method.

The radio signal transmitted from a mobile terminal is received at a radio base station and the received signal directly or externally modulates optical signal intensity. The optical signals are fed into an optical fiber through the optical switch. In the fiber, many PAM/IM signals gathered from many radio base stations are multiplexed by the TDMA method. These signals are transmitted to one of the optical switching nodes. Each PAM/IM signal is routed to its destination. At the destination, the received optical PAM/IM/TDMA signal is detected by a photodetector and the PAM/IM/TDMA optical signal reproduces the radio PAM signal. The radio PAM signal is converted into an actual radio signal by the appropriate bandpass or lowpass filtering.

In this system, PAM/IM/TDMA signals are switched at the routing nodes, so each PAM/IM burst should be accompanied by some identification tag that shows the destination, cell or intermediate routing node. The asynchronous transfer mode is one example of how radio High-way routing can be realized. Note that the sampling frequency is very low when the radio signals have restricted bandwidth [2], [3].

PAM/IM/TDMA networks have other distinctive features apart from network universality. One merit is that the system can connect a large number of base stations with one bus. Another merit is that the system has more handling capacity than conventional SCM systems [14]–[16]. SCM (subcarrier multiplexing) is the conventional method in that radio signals are subcarrier multiplexed in the radio frequency domain, and the radio multiplexed signal modulates the optical carrier. In the SCM system, laser diode nonlinearity produces intermodulation products among subcarriers. On the other hand, the PAM/IM/TDMA system has few radio signals, so the intermodulation products are relatively small compared to the conventional systems.

The relation between base station number that can be connected on the same bus and required laser diode power was theoretically calculated. The results are shown in Fig. 8. This figure shows that the TDMA multiplexing method can

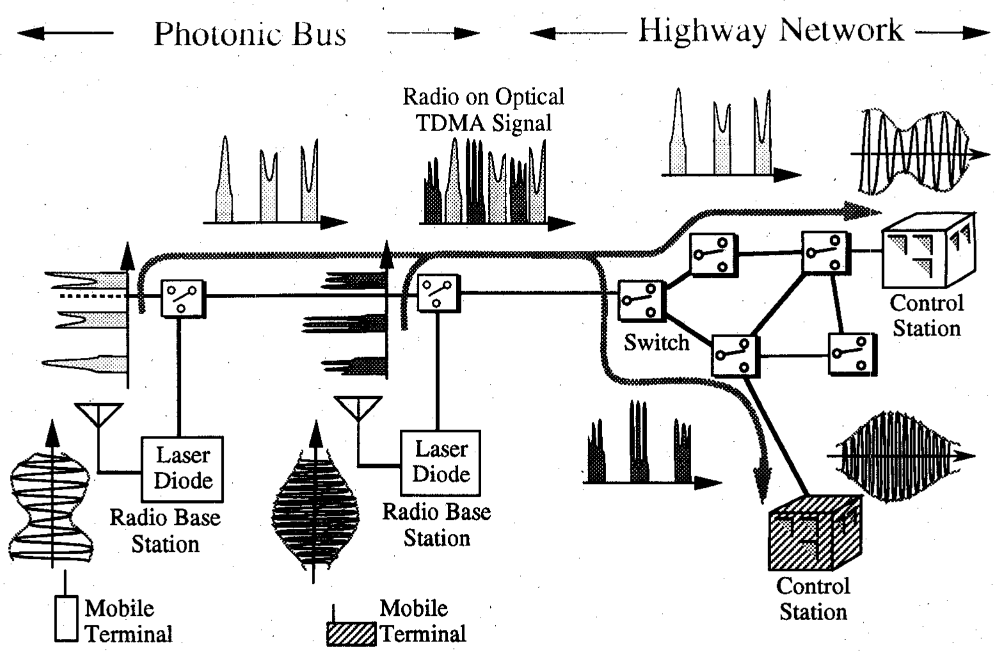

Fig. 8. Base station number and required optical power.

reduce the transmitting optical power while permitting large numbers of base stations.

Available capacity of the PAM/IM/TDMA system was calculated considering various radio signal modulation formats, and the results are shown in Fig. 9. It shows that the capacity of the PAM/IM/TDMA system is about six times greater than that of the conventional SCM system, because the number of radio carriers is reduced by the TDMA method and the intermodulation noise is reduced.

VI. Radio-Wave Photonic Devices Requirements to Realize TDMA Radio Highway

To realize the Radio High-way Network, device requirements must be specified. In Table I, requirements for photonic devices are summarized in a comparison with the photonic FDMA system. For laser diodes, TDMA permits the use of normal LD's because it does not require high frequency and phase stability. For photonic modulation, TDMA accepts either direct modulation or external modulation, while FDMA must use external FM or PM modulation to stabilize the optical frequency. For bus connection, TDMA can use low-loss switches, while FDMA requires large loss couplers or frequency duplexers. For networking switches, TDMA can use photonic switches, while FDMA requires hard-to-realize frequency converters. For the receiver, TDMA allows normal photodetectors and radio-band bandpass filters; FDMA requires frequency demultiplexers or photonic coherent detectors.

As shown above, this TDMA system is rather simple compared to the FDMA method and should have linear switching devices, a subject for further study.

VII. Conclusion

In this paper, we have proposed the Radio High-way Network, which effectively realizes universal radio base stations and seamless global cell connections. The network realizes the virtual free space. To construct the Radio High-way Network, we selected the photonic TDMA method. The number of base stations supported by each bus connection and available capacity were determined. From the analysis, the following were clarified:

1) The radio-wave photonic devices are key elements to realizing the universal mobile network for various multimedia communication services.
2) Mobile radio frequencies will continue to increase to the upper UHF, SHF, and lower EHF bands. The radio-wave photonic devices should operate in these bands.
3) TDMA photonic connection and self routing are suitable and no common control channel is needed between radio terminal and optical routers. The system can increase

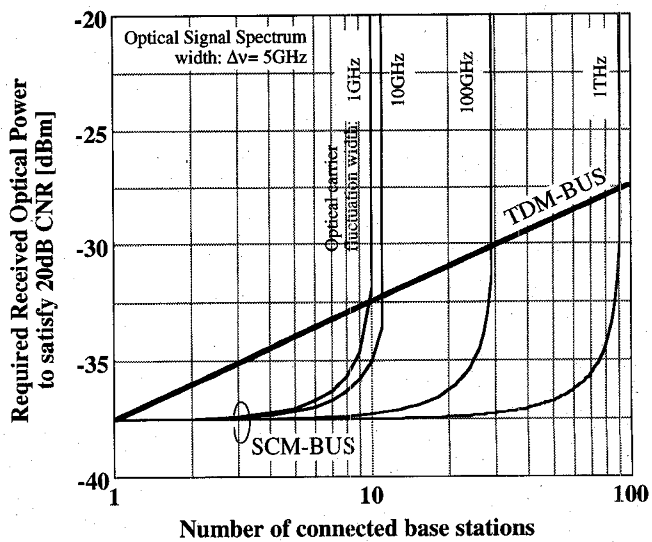

Fig. 9. Capacity of proposed network.

the number of radio base stations on the same bus link and can significantly improve the available capacity compared the conventional Subcarrier Multiplexing system.

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