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Comparison of microwave and light wave communication systems in space applications

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Abstract. The performances of optical and radio frequency communication systems are compared for long distance applications, such as deep space communications, where the signal-to-noise ratio (SNR) is crucial. We compare an optical communication system operating at 0.8 μm using intensity modulation and direct detection with an avalanche photodiode, an optical communication system operating at 1.5 μm using on-off keying and an optical preamplifier, and a radio frequency communication system operating in the X band. Assuming typical system parameters for the link budget analysis, we find that for distances between the transmitting and receiving antennas (R) of 10^7 km, the SNR for the optical systems is proportional to R^{-4}, while for the radio frequency system it is always proportional to R^{-2}. The maximum data rate achievable with the radio frequency system is higher than that with the optical systems for distances beyond 10^8 km. For near-Earth communication links, an optical system with optical preamplification is preferable when the data rate is higher than several gigabits per second. Clearly our results are based on specific system parameters. However, the equations involved and the method of comparison will be applicable for a wide range of system parameters.
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Subject terms: optical communications; radio frequency communications; intensity modulation and direct detection; avalanche photodiode; erbium-doped fiber amplifier; signal-to-noise ratio; deep space communications.

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1 Introduction

The advantages of optical communication systems over radio frequency (RF) systems include a wider bandwidth, a larger capacity, lower power consumption, more compact equipment, greater security against eavesdropping, and immunity from interference.[1] Although there have been some in-orbit demonstrations,[2–4] maintaining a line of sight between the transceivers is particularly difficult because of the small divergence angle of laser beams. Optical communication systems are expected to play a role in space communications,[1,5,6] and optical technologies for satellite networks are expected to revolutionize space system architectures.[7] It is thus important to investigate the appropriate characteristics of such communication systems and to identify which communication systems are best suited for the various configurations of space networks. One characteristic of basic optical reception, direct detection (DD), is that the electrical power of the signal is proportional to the square of the received optical power.[8] This is in contrast to RF systems where the electrical power of the signal is proportional to the received RF power.[9] The received optical power is inversely proportional to the square of the link distance, and the signal-to-noise ratio (SNR) with optical systems degrades more quickly with the distance than with RF systems. The SNR of an optical communication system using intensity modulation (IM) and DD with an avalanche photodiode (APD) is expected to be less than that of a RF system at long distances.[10]

We investigated two optical communication systems: one using IM with an APD receiver and one using IM with an erbium-doped fiber amplifier (EDFA) as an optical preamplifier. This paper is organized as follows: In Sec. 2, the SNR for the optical system with the APD receiver is described and the optimum APD gain is derived as a function of the communication link distance. The signal and noise for an optical system with an optical preamplifier and the resulting SNR are discussed in Sec. 3. A RF communication system operating in the X band is described and the SNR for the RF system is given in Sec. 4. The three systems are then compared, and the crossover distances of the data rates and SNRs are presented in Sec. 5.

2 Optical System with APD Detector

2.1 *Signal and Noise versus Distance (APD Reception)*

The electrical power of the received optical signal is proportional to the mean squared APD current, which can be written as[8]

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$$\langle i_{APD}^2 \rangle = (R_0 P_r M)^2, \tag{1}$$

where

$$P_r = P_t \tau_t G_t L G_r \tau_r \tag{2}$$

and

$$R_0 = \frac{\eta q \lambda}{hc}, \tag{3}$$

where R_0 denotes the primary sensitivity of the APD, P_r is the received power, M is the APD gain, η is the quantum efficiency, q is the electron charge, h is Planck's constant, c is the speed of light, τ_t is the transmission loss of the transmitter, τ_r is the transmission loss of the receiver, and λ is the wavelength. The G_t and G_r are the transmitter and receiver gain, and L is the space loss

$$G_t = \left(\frac{\pi D_t}{\lambda} \right)^2, \tag{4}$$

$$G_r = \left(\frac{\pi D_r}{\lambda} \right)^2, \tag{5}$$

and

$$L = \left(\frac{\lambda}{4\pi R} \right)^2, \tag{6}$$

where D_t and D_r are the antenna diameters for the transmitter and receiver, and R is the distance between them. The received power is thus

$$P_r = P_t G_t \tau_t G_r \tau_r \left(\frac{\lambda}{4\pi} \right)^2 \left(\frac{1}{R^2} \right), \tag{7}$$

and hence is proportional to R^{-2}. The noise contributions (i.e., the mean-square values of the APD current) are shot noise:

$$\sigma_{sig\text{-}shot}^2 = 2q(R_0 P_r) M^{x+2} B, \tag{8}$$

surface leakage current noise:

$$\sigma_{surf}^2 = 2q I_L B, \tag{9}$$

multiplied dark current noise:

$$\sigma_{dark,m}^2 = 2q(I_D) M^{x+2} B, \tag{10}$$

and Johnson noise:

$$\sigma_{johnson}^2 = \frac{4kTBF_T}{R_{eq}}, \tag{11}$$

where I_D is the bulk dark current, I_L is the surface leakage current, $F(M) \approx M^x (0 \leqslant x \leqslant 1)$ is the excess noise factor, k is the Boltzmann constant, B is the equivalent noise bandwidth, R_{eq} is the equivalent circuit resistance, F_T is the noise figure of the electric circuit, and T is the system temperature. The SNR for the optical communication system is thus given by

Table 1 Parameters for an optical communication link with APD detector.

Parameter	Value
Transmitter transmission loss, τ_t	0.5
Receiver transmission loss, τ_r	0.5
Transmitter antenna diameter, D_t	30.5 cm
Receiver antenna diameter, D_r	10.0 m
Wavelength, λ	0.85 μm
Transmitter power, P_t	0.1 W
APD quantum efficiency, η	0.6
Excess noise parameter, x	0.5
Bulk dark current, I_D	0.05 nA
Surface leakage current, I_L	0 A
Equivalent resistance, R_{eq}	50 kΩ
Electrical bandwidth, B	25 MHz
Noise figure, F_T	3 dB
System temperature, T	290 K

$$SNR_{APD} = \frac{(R_0 P_r M)^2}{2q(R_0 P_r + I_D) M^{x+2} B + 2q I_L B + 4kTBF_T / R_{eq}}. \tag{12}$$

If shot noise dominates, we have

$$SNR_{APD}|_{shot} = K_1 R^{-2}, \tag{13}$$

where

$$K_1 = P_t G_t \tau_t G_r \tau_r \left(\frac{\lambda}{4\pi} \right)^2 \frac{R_0}{2qM^x B}. \tag{14}$$

If Johnson noise dominates, the SNR is given by

$$SNR_{APD}|_{Johnson} = K_2 R^{-4}, \tag{15}$$

where

$$K_2 = \left[P_t G_t \tau_t G_r \tau_r \left(\frac{\lambda}{4\pi} \right)^2 \right]^2 \frac{(R_0 M)^2 R_{eq}}{4kTBF_T}. \tag{16}$$

The signal and noise contributions of an IM-DD optical communication link are calculated using the parameters shown in Table 1. System parameters are based on Semiconductor Intersatellite Laser Experiment (SILEX) technology.[3] A transmitter antenna diameter of 30.5 cm is used because this diameter is used in the Mars Telecommunications Orbiter.[11] A receiver antenna diameter of 10 m is used because that is a typical diameter for photon buckets for deep space on the ground.[12] Atmospheric attenuation is neglected for simplicity. To benefit from the highest pos-

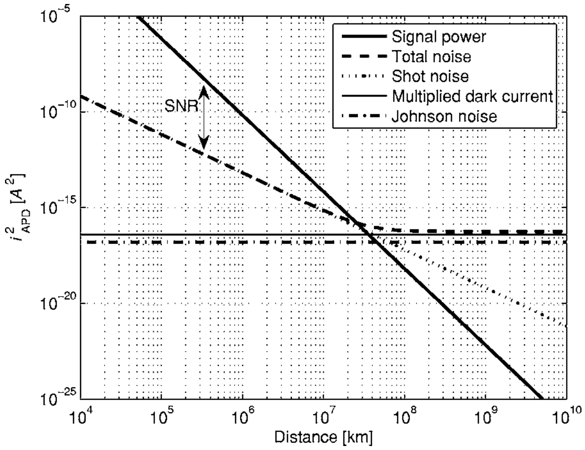

Fig. 1 Electrical signal and noise powers versus distance when $M = 100$.

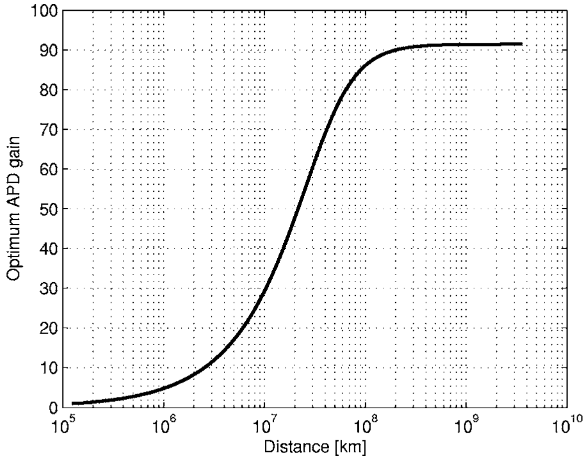

Fig. 2 Optimum APD gain, M_{opt}, as a function of distance.

sible sensitivity of APD detection, a wavelength of 0.85 μm is taken. The electrical bandwidth of $B = 25$ MHz will allow a data rate of some 50 Mbit/s. Figure 1 illustrates the electrical signal power and noise contributions as a function of the distance when the APD gain $M = 100$. Johnson noise is dominant beyond distances of 10^8 km and the multiplied dark current dominates when M becomes high. The dependence of the SNR on the distance gradually changes from R^{-2} to R^{-4} as the distance increases. When M is small, the dark current noise is lower than the Johnson noise, and then the SNR is limited by the Johnson noise at longer distances.

2.2 *Optimum Value of APD Gain*

The SNR given by Eq. (12) can be rewritten as

$$SNR_{APD} = \frac{C_1 M^2}{C_2 M^{x+2} + C_3}, \tag{17}$$

where

$$C_1 = (R_0 P_r)^2, \tag{18}$$

$$C_2 = 2q(R_0 P_r + I_D)B, \tag{19}$$

and

$$C_3 = 2qI_L B + 4kTBF_T/R_{eq}. \tag{20}$$

To find the maximum SNR (and the corresponding APD gain), we calculate

$$\frac{d(SNR_{APD})}{dM} = \frac{C_1 M(-xC_2 M^{x+2} + 2C_3)}{(C_2 M^{x+2} + C_3)^2}, \tag{21}$$

and find the optimum APD gain, M_{opt}

$$(-xC_2 M_{opt}^{x+2} + 2C_3) = 0 \tag{22}$$

and

$$M_{opt} = \left[\frac{2qI_L + (4kTF_T/R_{eq})}{xq(R_0 P_r + I_D)} \right]^{1/(x+2)}. \tag{23}$$

Figure 2 shows the optimum APD gain as a function of distance when the parameters in Table 1 are used. When shot noise is dominant, the optimum APD gain is rather small. For long distances, where shot noise is negligible, the optimum APD gain approaches 91, which is mainly determined by the bulk dark current. Substituting M_{opt} into Eq. (12) yields the maximum SNR:

$$SNR_{APD}|_{\max} = \frac{(R_0 P_r)^2}{(x+2)B} \left[\frac{1}{q(R_0 P_r + I_D)} \right]^{2/(x+2)} \times \left(\frac{x}{2qI_L + 4kTF_T/R_{eq}} \right)^{x/(x+2)}. \tag{24}$$

The APD gain is set to its optimum value $M_{opt}(R)$ in the following discussion.

3 Optical System with EDFA Preamplifier

3.1 *Signal and Noise versus Distance (Optically Preamplified Reception)*

We assume that an EDFA is used as a booster amplifier in the transmitter and as a low noise preamplifier in the receiver. The electrical power of the received signal is proportional to the mean-squared current generated by the photodiode following the optical preamplifier; it can be written as

$$\langle i_{EDFA}^2 \rangle = (R_0 G_0 P_r)^2, \tag{25}$$

where G_0 is the gain of the optical preamplifier. From the many noise contributions in an optical receiver incorporating an EDFA, only a few will dominate if it is well designed.[13–15] These are amplified spontaneous emission (ASE) self-mixing noise (ASE × ASE):

$$\sigma_{ASE\times ASE}^2 = 2[qn_{sp}\eta(G_0 - 1)]^2 B(2B_0 - B), \tag{26}$$

ASE noise mixed with the signal ($S \times$ ASE):

$$\sigma^2_{S\times ASE} = 4R_0 q n_{sp}\eta G_0(G_0-1)P_r B, \tag{27}$$

background radiation mixed with the signal ($S\times$ back):

$$\sigma^2_{S\times back} = 4R_0^2 G_0^2 P_r N_b B, \tag{28}$$

and Johnson noise:

$$\sigma^2_{johnson} = \frac{4kTBF_T}{R_{eq}} = i_n^2 B, \tag{29}$$

where i_n is the electrical preamplifier noise current density. Equations (26) and (27) take into account both polarization states in the ASE noise. Assuming that $G_0 \gg 1$ and reasonably high input powers, the spontaneous emission factor is given by

$$n_{sp} \approx \frac{F_n}{2}, \tag{30}$$

where F_n is the noise figure of the optical preamplifier. The background radiation power spectral density, N_b, is the sum of the background radiation produced by celestial bodies and the transmit booster ASE. It can be approximated by

$$N_b = N_{celestial\ bodies} + \frac{0.3hcG_{TX}F_{TX}D_t^2 D_r^2}{R^2\lambda^3}, \tag{31}$$

where G_{TX} denotes the gain of the transmit optical amplifier and F_{TX} is the noise figure of the transmit amplifier. The total noise can be written as

$$\sigma^2_{total} = \sigma^2_{S\times ASE} + \sigma^2_{ASE\times ASE} + \sigma^2_{S\times back} + \sigma^2_{johnson}. \tag{32}$$

The SNR for optically preamplified reception is thus

$$SNR_{EDFA} = \frac{(R_0 G_0 P_r)^2}{4P_r B R_0 G_0[q n_{sp}\eta(G_0-1) + R_0 G_0 N_b] + 2B(2B_0 - B)[q n_{sp}\eta(G_0-1)]^2 + 4kTBF_T/R_{eq}}. \tag{33}$$

If in the noise terms the beat noise $S\times$ back dominates, the SNR is independent of distance, that is,

$$SNR_{EDFA}|_{back} = \frac{P_t\tau_t\tau_r\pi^2\lambda}{4^3 B(0.3hcG_{TX}F_{TX})}. \tag{34}$$

When $S\times$ ASE noise is dominant, as it would be for ideal reception,

$$SNR_{EDFA}|_{S\times ASE} = K_3 R^{-2}, \tag{35}$$

where

$$K_3 = \left[P_t G_t \tau_t G_r \tau_r \left(\frac{\lambda}{4\pi}\right)^2\right] \frac{R_0 G_0}{4B[q n_{sp}\eta(G_0-1)]}. \tag{36}$$

When ASE $\times$ ASE noise is dominant,

$$SNR_{EDFA}|_{ASE\times ASE} = K_4 R^{-4}, \tag{37}$$

where

$$K_4 = \left[P_t G_t \tau_t G_r \tau_r \left(\frac{\lambda}{4\pi}\right)^2\right]^2 \frac{(R_0 G_0)^2}{2B(2B_0 - B)[q n_{sp}\eta(G_0-1)]^2}. \tag{38}$$

When Johnson noise is dominant,

$$SNR_{EDFA}|_{Johnson} = K_5 R^{-4}, \tag{39}$$

where

$$K_5 = \left[P_t G_t \tau_t G_r \tau_r \left(\frac{\lambda}{4\pi}\right)^2\right]^2 \frac{(R_0 G_0)^2 R_{eq}}{4kTBF_T}. \tag{40}$$

The signal and the noise contributions for a link with optical preamplification were calculated using the parameters shown in Table 2. These parameters are mostly those used in Refs. 13 and 15. Background radiation caused by the sun would be the worst case. Still, because of the tight spatial filtering by the single-mode fiber in the optical preamplifier, this does not lead to a significant noise contribution. An example of the optical signal and noise contributions as a function of distance is shown in Fig. 3. The transmit booster ASE would dominate at distances up to 10^5 km, causing the SNR to be independent of R. For distances between 10^5 and 10^7 km the SNR is determined by the $S \times$ ASE noise and shows an R^{-2} dependence. The ASE $\times$ ASE noise is dominant at distances beyond 10^7 km and the SNR then becomes proportional to R^{-4}.

4 SNR for RF Communication System versus Distance

For the RF link, the Johnson noise for a system at temperature T is given by

$$\sigma^2_{johnson} = \frac{4kTBF_T}{R_{eq}}, \tag{41}$$

and the SNR is

$$SNR_{RF} = \frac{P_r/R_{eq}}{4kTBF_T/R_{eq}} = \frac{P_t G_t \alpha_t G_r \alpha_r}{4kTBF_T}\left(\frac{\lambda}{4\pi}\right)^2\left(\frac{1}{R^2}\right), \tag{42}$$

where α_t and α_r are the RF antenna efficiencies for the transmitter and receiver. The SNR of the RF signal is al-

Table 2 Parameters for an optical communication link with optical preamplifier.

Parameter	Value
Transmitter transmission loss, τ_t	0.5
Receiver transmission loss, τ_r	0.5
Transmitter antenna diameter, D_t	30.5 cm
Receiver antenna diameter, D_r	10.0 m
Wavelength, λ	1.56 μm
Transmitter power, P_t	1.0 W
Transmit booster gain, G_{TX}	33 dB
Transmit booster noise figure, F_{TX}	6 dB
Quantum efficiency, η	0.5
Optical preamplifier gain, G_0	30 dB
Optical amplifier noise figure, F_n	3.8 dB
Spontaneous emission factor, n_{sp}	1.2
Optical bandwidth, B_0	0.60 nm (corresponding to 74 GHz)
Electrical preamplifier noise current density, i_n	12 pA/$\sqrt{\text{Hz}}$
Electrical bandwidth, B	25 MHz
Background radiation from celestial bodies, $N_{celestial\ bodies}$	6×10^{-20} W/Hz (receiver looks directly into the sun)

ways proportional to R^{-2}, in contrast to the dependence found in optical systems. Typical parameters for deep space communication links operating in the X band are shown in Table 3. Following Ref. 10, the system parameters were chosen with a view to the GEOTAIL spacecraft, which was developed by Japanese Aerospace Exploration Agency (JAXA) and National Aeronautics and Space Administration (NASA) and launched in 1992 to explore the geomagnetic tail. More specifically, a transmit antenna diameter of 1.6 m and a transmit power of 65 W are chosen, as Mars Express uses these values for communication at X band.[16] For the receive antenna diameter we take D_r=64 m, that is the value available at the Usuda Deep Space Center.

5 Comparison of SNR and Data Rate versus Distance

The SNRs of the two optical systems are compared with that of the RF system in Fig. 4. An electrical bandwidth of 25 MHz was used for all these systems. Past 10^8 km, the RF system achieves the best SNR. Between 10^5 to 10^8 km, approximately corresponding to the moon to Mars, respecitvely, the optical system with EDFAs has the best SNR. At a distance of around 10^4 km corresponding to GEO-to-ground-station distance, all three systems achieve sufficient SNR.

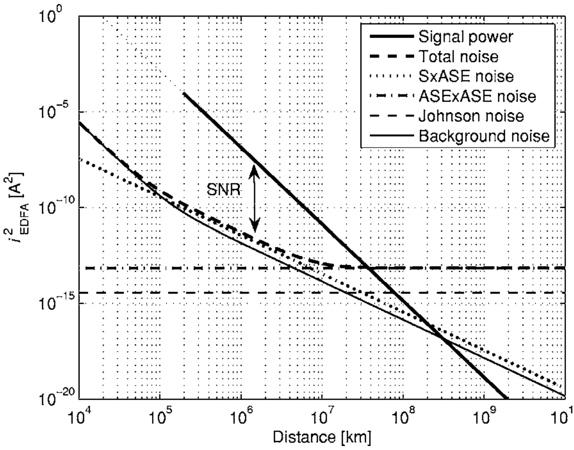

Fig. 3 Electrical signal and noise powers versus distance for an optical link equipped with EDFAs.

The maximum achievable data rates for the optical and RF communication systems as a function of distance are shown in Fig. 5. An SNR of 16.6 dB, leading to a bit error ratio (BER) of 10^{-6}, is used, Ref. 17. For this calculation, the data rate (in bits per second) is assumed to be 1.4 times the electrical bandwidth B (in Hertz).[18,19] For near-Earth communication links, the optical systems can achieve data rates of several gigabits per second. The data rate of the RF system will be lower because it is limited by the RF carrier frequency of 8.47 GHz. The optical system using the optimum APD gain allows the data rate of several gigabits per second for near Earth distances, limited by the response of available APD detectors.[20] The optical communication system with EDFAs is suitable not only for a high-data-rate, short-range communication links but also for links up to the Mars. The crossover in performance between the RF and

Table 3 Typical parameters for an RF communication system.

Parameter	Value
Transmitter antenna efficiency, α_t	0.5
Receiver antenna efficiency, α_r	0.7
Transmitter antenna diameter, D_t	1.6 m
Receiver antenna diameter, D_r	64 m
Wavelength, λ	3.54 cm
Transmitter power, P_t	65 W
Equivalent registance, R_{eq}	50 kΩ
Noise figure, F_T	3 dB
System temperature, T	290 K

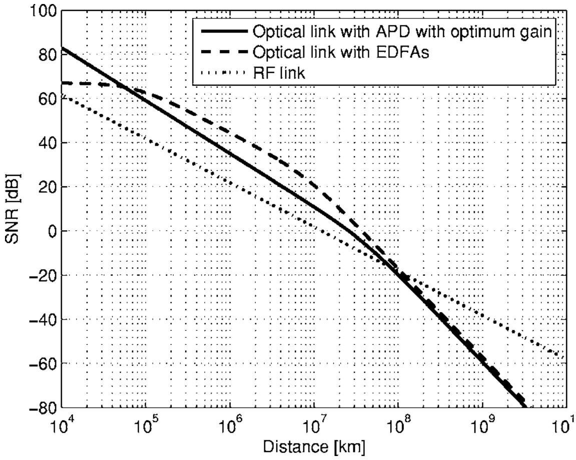

Fig. 4 SNRs of optical systems with APD receiver or EDFAs and of a RF system operating in the *X* band as a function of communication link distance.

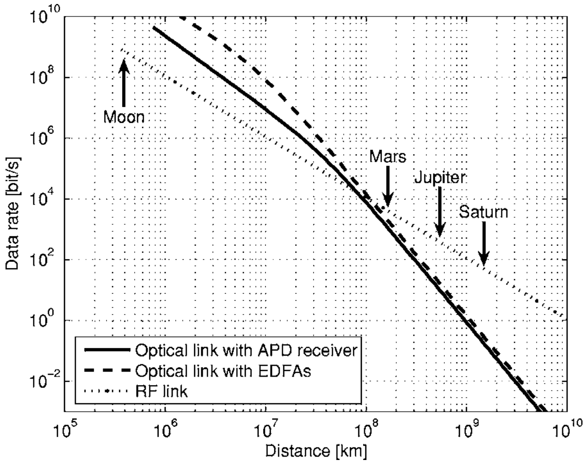

Fig. 5 Maximum data rates for optical and RF communication systems as a function of link distance.

optical systems occurs at around 10^8 km if typical system parameters are used. The RF communication system might be preferable for the Mars-to-Earth link of 1.5×10^8 km. However, in addition to the link budget results, onboard requirements should be taken into account when identifying the most suitable system. In this respect, the modulation scheme, mass, power, and volume, as well as regulatory restrictions are important factors. The new development of high power laser sources will help to enhance the data rate. Further, in optical communication systems for deep space applications, error correcting codes with high gain and special modulation schemes, such as a pulse position modulation (PPM) signaling, may eventually help to achieve higher data rates than that of RF systems,[21,22] (this paper does not cover such implementations). However, the RF communication system will be preferable beyond the Jupiter- or Saturn-to-Earth distance links because the optical systems obey an R^{-4} dependence as well. Sooner or later, we might abandon the use of optical systems for much longer distances.

As can be seen from the above discussion, the RF system is currently the most suitable one for very long distance communications. The application of optical communication systems to long-distance links requires the development of new technologies. One could think of using coherent homodyne detection in connection with phase shift keying.[23] However, this transmission scheme asks for highly stable lasers both in the transmitter and—as local oscillator—in the receiver and requires a complicated device for beam combination. Another improvement in optical links can be expected to result from ongoing research in the field of quantum communication technology. Recently, a communication capacity beyond the classical capacity limit has been achieved employing a so-called quantum circuit in the receiver.[24,25] However, one of the problems of photon-based quantum schemes is that entangled photons cannot be cloned and, hence, also cannot be amplified.[26] Further progress in the area of quantum physics might open new possibilities for photonic long distance communications.

6 Conclusion

Achievable data rates of RF and optical communication systems were compared as a function of the communication link distance, using system parameters based on currently available technologies for the link budget analyses. Despite the fact that only very specific parameters were considered for the communication systems, the RF communication system tends to be better suited for distances beyond 10^8 km. An optical system with optical preamplification is best suited for high-data-rate, near-Earth communication links. The choice of a suitable space communication system must also take into account the terminals' mass, power, volume, regulatory restrictions, and such RF communication systems will be preferable in deep space communication links for the time being, maybe until coherent and quantum communications technology makes a big leap forward.

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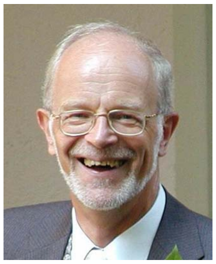

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