The Square Kilometre Array as a "Direct-to-Earth" facility for deep space communications

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Abstract

The extremely high sensitivity of the Square Kilometre Array (SKA) will make possible Direct-to-Earth (DtE) communications from distant spacecraft within the range of the Solar System. DtE could become a valuable addition to standard communication schemes supporting special science tasks or mission-critical operations. It could also serve as an important back-up option for the "traditional" configurations based on dedicated deep space communication facilities. Several estimates for different missions, transmitter power and modulation schemes are presented.

1. Introduction

Communication with deep space missions usually employs dedicated Earth-based facilities equipped with large antennae (such as the NASA Deep Space Network, DSN). The most commonly used scheme is that of duplex communication. High gain antennae and powerful transmitters onboard spacecraft (S/C) allow communication to be maintained up to the edge of the Solar System. However, the radio link system imposes serious restrictions on mission operations. The restrictions grow rapidly with increasing distance to the spacecraft. These restrictions are particularly severe for short-lived planetary probes. In most cases, planetary probes relay science and housekeeping telemetry data via orbiters or flyby S/C. Usually, such a scheme requires buffering the probe's data onboard the relay S/C. The Cassini–Huygens mission is an example of such a communication scheme: the Huygens Probe communicated data from the descent phase of the mission to Titan via the Cassini spacecraft. As was demonstrated by the Huygens mission, an ad-hoc direct receipt of the carrier signal by Earth-based radio telescopes turned out to be a valuable asset and contributed to the overall success of the mission (Lebreton et al. 2005).

In the traditional relay scheme, a planetary probe is equipped with a low-gain antenna roughly oriented toward the relay S/C and not necessarily toward the Earth. The probe's transmitter power is limited to several watts (typically < 5 W). Such a low power link makes it practically impossible to provide down-link to Earth from the probe using any of the existing DSN-style facilities or presently operational radio telescopes (beyond detecting a carrier signal, and even this with considerable difficulties).

An alternative to the traditional relay scheme is a Direct-to-Earth (DtE) communication method. It brings in a number of advantages, especially in the case of communicating data from planetary probes – landers, penetrators, atmosphere and surface vehicles, etc. DtE makes unnecessary an extremely costly mission component, a relay S/C. Even if the role of the relay S/C is performed by an indispensable probe carrier (e.g. as the Cassini S/C in the aforementioned Cassini-Huygens mission), the relay scheme imposes severe ballistic restrictions and other operational limitations; in particular, on timing and duration of the broadcast from the probe. All in all, the relay scheme is responsible for a very considerable fraction of the cost of one bit of scientific data delivered from the probe to Earth. Of course, the relay scheme enables a considerably higher amount of data to be delivered from the probe to Earth than can be provided by DtE. But DtE can be considered as a backup to the relay scheme, especially during critical events of a probe's science programme.

Recently major space agencies began to assess design options for the next-generation planetary probes. These missions are expected to begin in-situ operations around 2020 or later. In Europe, under ESA's Cosmic Vision programme, a number of proposals call for multi-spacecraft missions, with probes going to Titan (TandEM and TSSM study, Coustenis et al. 2008), Europa (Laplace and EJSM study, Blanc et al. 2008), and Venus (EVE, Chassefire et al. 2008). Another class of missions include deep-diving probes into dense atmospheres of giant planets, e.g. the Kronos mission, proposed under the Cosmic Vision programme (Marty et al. 2008). This mission aims to study the Saturn atmosphere in-situ at the pressure level of ~ 10 bar. Communication from such a probe is particularly difficult due to a considerable attenuation of the signal in dense atmosphere. Since attenuation grows with frequency, the probe broadcasts at frequencies below 1 GHz, the range at which radio telescopes are much more sensitive than standard DSN facilities. In all the cases above, the probes will broadcast at relatively low frequencies, certainly not higher than 8 GHz, making them suitable targets for radio telescopes operating at well established radio astronomy GHz bands.

The huge effective area of the Square Kilometre Array (SKA) would enable Direct-to-Earth (DtE) communication from a distant S/C located practically anywhere in the Solar System. The case for SKA as a S/C tracking facility is discussed by Jones (2004). Below we present estimates of SKA DtE options under various considerations for the probe's signal strength and modulation. Implicitly we consider DtE in the standard deep space communication frequency 2.3 GHz. However, the results presented below are practically invariant over a wide range of operational frequencies of SKA from hundreds of MHz to 10 GHz.

2. Radio link power budget and error bit rate

We analyse the SKA DtE communication scheme under the following assumptions:

1. The maximum distance from Earth to a probe is $R_{\max} = 10$ AU.
2. The communication is conducted in the standard frequency S- or X-bands.
3. The probe's transmitter power, P_{tr} is equal to 1, 3 or 5 W.

4. The probe's antenna is omnidirectional (i.e., antenna gain $G = 1$).
5. The SKA's effective area is $A_{\text{eff}} = 5 \times 10^5$ m^2.
6. The system noise temperature of SKA is $T_{\text{sys}} = 50$ K.

The SKA characteristics above (items 4–5) represent a conservative set of values. The actual SKA parameters might be considerably better at frequencies around 1 GHz (Schilizzi et al. 2007). The SKA will also have a superb sensitivity at frequencies below 1 GHz. This range of decimetre to metre wavelengths might be useful for DtE from planetary probes diving deep into atmospherees of giant planets or "eavesdropping" on "probe-to-orbiter" transmission from planets (e.g. at the standard frequency of 430 MHz).

The signal-to-noise ratio for the received signal in the bandwidth equal to 1 Hz is

$$SNR_{\text{power}} = \frac{P_{tr}GA_{\text{eff}}}{4\pi R^2 kT_{\text{sys}}}, \qquad k = 1.23 \times 10^{-23} \text{ J/K}. \tag{1}$$

The potential transmission bit rate can be estimated using the Shannon's formula for channel information throughput with the bandwidth ΔF and a given SNR as:

$$C = \Delta F \log_2(1 + \frac{SNR_{\text{power}}}{\Delta F}) \quad , \tag{2}$$

Fig. 1a shows the transmission bit rate as a function of bandwidth for three distances to the probe $R = 5.0, 7.5, 10$ AU and the transmitter power $P_{\text{tr}} = 1$ W. Fig. 1b shows similar characteristics but for the transmitter power $P_{\text{tr}} = 1, 3, 5$ W and $R = 10$ AU. The values presented on Fig. 1a, b are the theoretical upper limits. In reality, the achievable values are lower due to non-ideal characteristics of the devices along the signal path.

In general, there is a trade-off between the required transmitter power and bandwidth of transmission for a given amount of data to be delivered from a planetary probe. However, both parameters are limited. In order to optimise the use of the communication radio link, different modulation and coding schemes are implemented.

A digital modulation scheme with phase-shift keying (PSK) is widely used in communication systems (Yuen et al. 1990). It provides both a low Bit-Error-Rate (BER) and minimum bandwidth. For the case of the binary phase-shift keying (BPSK), BER can be estimated as follows:

$$P_{\text{BER,BPSK}} = Q(\sqrt{2 \times SNR_{\text{bit}}}), \tag{3}$$

where

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int\limits_{x}^{\infty} e^{\frac{-t^2}{2}} dt, \tag{4}$$

$SNR_{\text{bit}} = SNR_{\text{power}} \times T = \frac{SNR_{\text{power}}}{RW}$ is the signal-to-noise ratio per bit, T is the duration of signal transmission per 1 bit and RW is the transmission rate.

Fig. 2a shows the BER as a function of the transmission rate (in bit/s) for the transmitter power $P_{\text{tr}} = 1$ W and three distances as parameters, $R = 5, 7.5, 10$ AU.

A significant gain in the transmission rate can be achieved by means of error-control coding (the so called *coding gain*). For example, in the case of block coding – an extended Golay code (24,12) – with a subsequent BPSK modulation, BER can be calculated as:

$$P_{\text{bit,Golay}} \approx \frac{1}{24} \sum_{m=4}^{24} m\binom{24}{m} p_{uc}^m (1 - p_{uc})^{24-m}, \tag{5}$$

where p_{uc} is the probability of error in an uncoded BPSK but with the $\frac{24}{12}$ times faster rate. The example in Fig. 2b shows a substantial improvement in the BER for the distance $R = 10$ AU with the extended Golay code (24,12) as a function of the transmission rate.

3. M-ary Orthogonal Signals, coherent MFSK

Another option for increasing the transmission rate is based on the use of M-ary orthogonal signals. Every binary sequence of the length k corresponds to one of the $M = 2^k$ orthogonal signals which modulate carrier signals.

In the following example, the M-ary *frequency shift keying* (MFSK) is used: each symbol corresponding to a particular binary sequence of the length k is transmitted on the m-th frequency during an interval T:

$$s_m(t) = A\cos[2\pi(f_c + m\Delta f)t], \qquad 0 \le t \le T, \qquad m = 1, 2, ...M, \tag{6}$$

where $\Delta f = 1/2T$, and T is the duration of a symbol. For example, for $k = 5$, there are 32 different orthogonal signals, each at its own frequency. The total bandwidth is $W = M\Delta f$. The effective transmission rate is $RW = k/T$, $k = log_2 M$. The ratio RW/W is called *bandwidth expansion*: $RW/W = (2log_2 M)/M$. Theoretically, by increasing M it is possible to reach the Shannon limit.

The probability of bit error for the *coherent* processing of $M = 2^k$ orthogonal signals can be calculated using the following expression (Proakis 2001):

$$P_{\text{BER,FSK\_C}} = \frac{2^{k-1}}{2^k - 1} \cdot \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} [1 - (\frac{1}{\sqrt{2\pi}} \int_{-\infty}^{y} e^{-\frac{t^2}{2}} dt)^{M-1}] \times$$

$$\times exp[-(y - \sqrt{2 \cdot SNR_{\text{symbol,FSK}}})^2/2]dy, \tag{7}$$

where $SNR_{\text{symbol,FSK}} = SNR_{\text{power}} \times T$, each signal will transmit k bits simultaneously.

Fig. 3a gives the probabilities of bit error for $M = 2, 4, 8, 16, 32$, $P_{\text{tr}} = 1$ W and $R = 10$ AU as a function of the transmission rate. Similar curves but for $M = 32$, $P_{\text{tr}} = 1$ W and different distances $R = 5, 7.5, 10$ AU are given in Fig. 4a.

Further improvement can be achieved by means of data coding. Fig. 4b illustrates the application of Reed-Solomon coding for the same M, P_{tr} as in Fig. 4a and $R = 10$ AU. The parameter $t = 1, 2, 4, 8$ is the number of symbol errors guaranteed to be corrected by the code. There is a considerable improvement for $t = 1, 2, 4$, but a characteristic crossover at low SNR (higher transmission rate) for $t = 8$ appears much earlier.

4. M-ary Orthogonal Signals, noncoherent MFSK

The probability of bit error for the *incoherent* processing of $M = 2^k$ orthogonal signals is calculated using the following expression:

$$P_{\text{BER,FSK\_NC}} = \frac{2^{k-1}}{2^k - 1} \sum_{n-1}^{M-1} (-1)^{n+1} \binom{M-1}{n} \frac{1}{n+1} \exp[-nSNR_{\text{symbol,FSK}}/(n+1)]. \quad (8)$$

As in Figs 3a, 4a, and 4b, Figures 3b, 5a, and 5b give similar probabilities of bit error as functions of the transmission rate for noncoherent MFSK.

5. Coding complexity

It is possible to achieve a near-Shannon error correction performance by increasing the coding complexity. Concatenation of convolutional codes with Reed-Solomon codes (Yuen et al. 1990) and implementation of the recently discovered new class of convolutional codes (*turbo codes*, Dolinar et al. 1998, Divsalar and Pollara 1995) provide an impressive coding gain. Fig. 6 shows how the transmission rate depends on the distance with the following turbo code: rate 1/2, block length=10200, 10 iterations: $P_{\text{tr}} = 1$ W, $SNR_{\text{bit}} = 1.0$ dB, $BER = 10^{-5}$. The curve for uncoded BPSK is also shown in this figure for $P_{\text{tr}} = 1$ W, $SNR_{\text{bit}} = 9.59$ dB, $BER = 10^{-5}$. A significant gain is clearly visible.

6. Conclusions

The analysis described in this memo indicates a significant potential of the SKA as a DtE facility. As the benchmark value, we note that at the communication frequency of 2.3 GHz (considered to be close to the band of maximum sensitivity for SKA), the turbo-coded DtE link can provide for a transmission rate of ~ 20 bps from a S/C at the distance of 8 AU (see Fig. 6).

In addition to the high sensitivity, illustrated by our calculations, the SKA offers instantaneous frequency coverage from ~ 100 MHz to ~ 10 GHz, unlike traditional DSN-style facilities, able to operate within relatively narrow dedicated frequency bands. Such a frequency agility might be an important asset for supporting communication from planetary probes as a mission back-up, e.g. similar to "eavesdropping" on the Huygens up-link communication to the Cassini spacecraft at the non-standard down-link at the frequency of 2040 MHz (Lebreton et al. 2005). Planetary probes for in situ studies of atmospheres of giant planets (e.g. Jupiter, Saturn) require communication at frequencies below ~ 1 GHz (see e.g. Marty et al. 2008). In this non-standard communication regime, the SKA might also become an indispensable asset.

We note that MFSK is also convenient for VLBI tracking since it is better suited for group delay measurements than a mono-chromatic carrier.

Our main conclusion is as follows:

The SKA will be able to receive digital information from a planetary probe or interplanetary S/C with a transmitter power of 1 W from a distance of up to 10 AU

with a transmission rate of several tens of bps using MFSK and an appropriate coding gain. A higher transmitter power of 3 to 5 W would further improve the link budget significantly.

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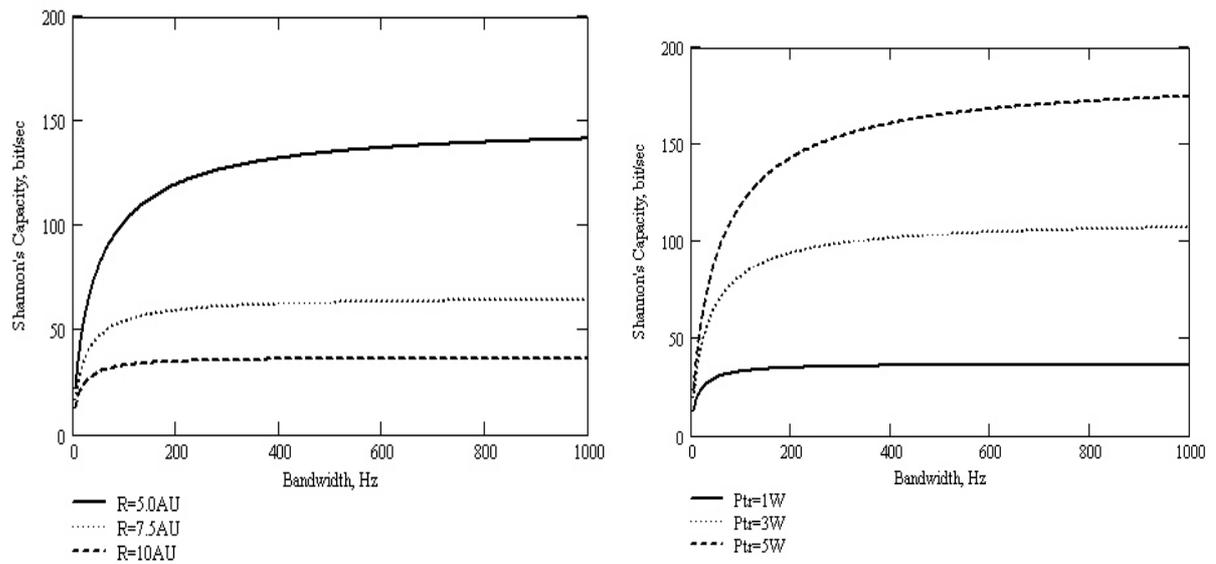
Figure 1: **Left panel (a):** the potential throughput of a DtE link as a function of bandwidth; the transmitter power $P_{tr} = 1$ W, the distance is a parameter. **Right panel (b):** the potential throughput of a DtE link as a function of bandwidth; the distance $R = 10$ AU, the transmitter power is a parameter.
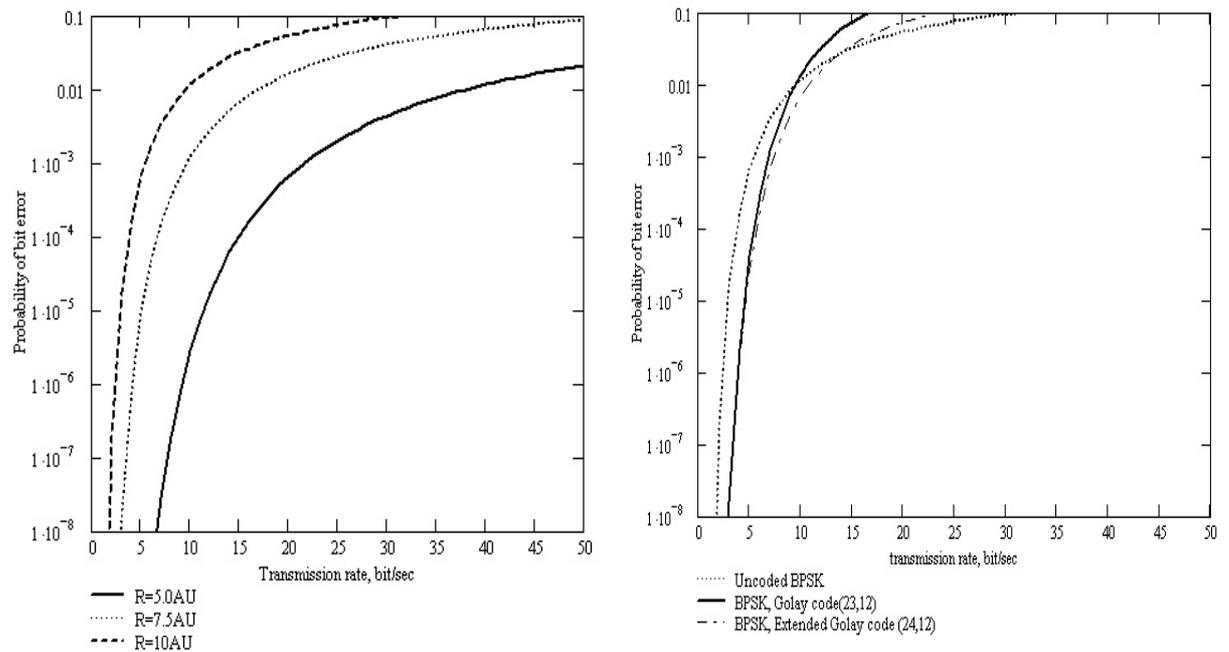

Figure 2: **Left panel (a):** BPSK, the bit error rate as a function of the transmission rate; the transmitter power $P_{tr} = 1$ W, the distance is a parameter. **Right panel (b):** BPSK with preliminary coding using the extended Golay code (24,12), all parameters are the same as in Fig. 2a.
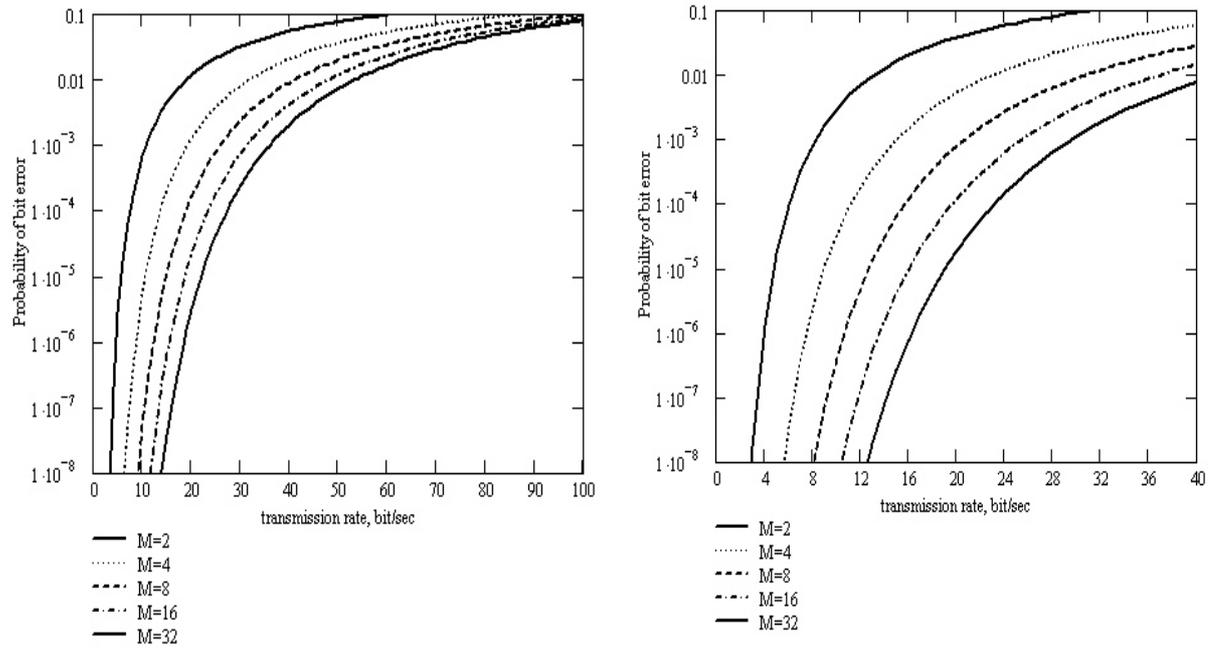
Figure 3: **Left panel (a):** Coherent MFSK, the bit error rate as a function of the transmission rate; the transmitter power $P_{\mathrm{tr}} = 1$ W, the distance $R = 5$ AU, the number of orthogonal signals M is a parameter; **Right panel (b):** Incoherent MFSK, all parameters are the same as in Fig. 3a.
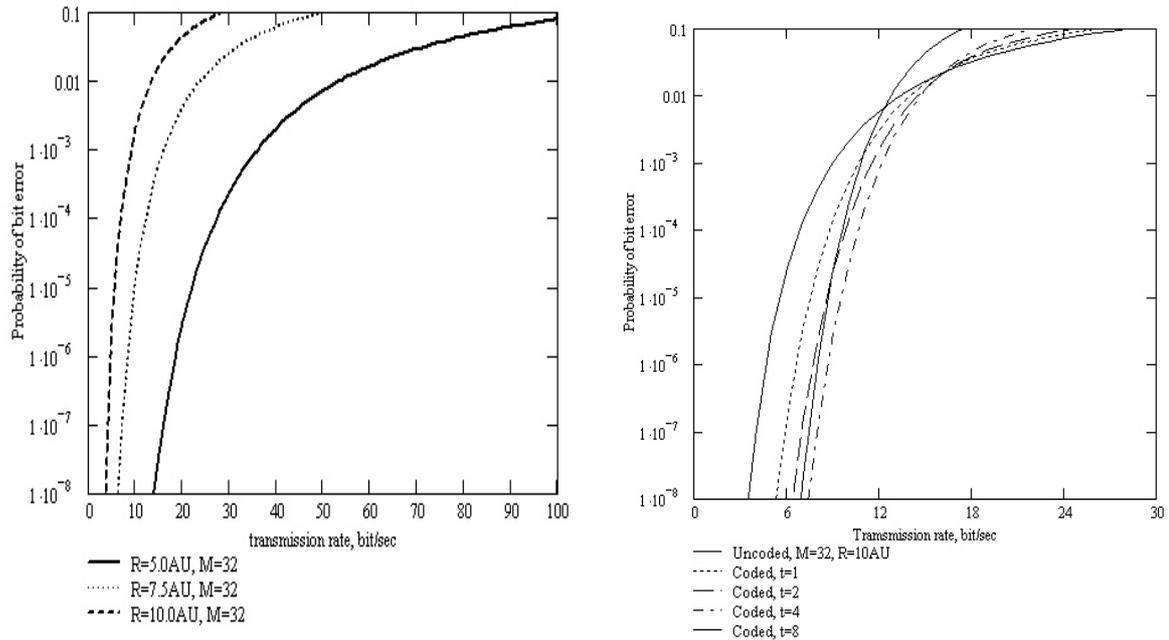

Figure 4: **Left panel (a):** Coherent MFSK, the bit error rate as a function of the transmission rate; the transmitter power $P_{tr} = 1$ W, $M = 32$, the distance is a parameter; **Right panel (b):** Coherent MFSK with the same parameters, the distance $R = 10$ AU and preliminary Reed-Solomon coding, the parameter t is the number of symbol errors guaranteed to be corrected by the code.
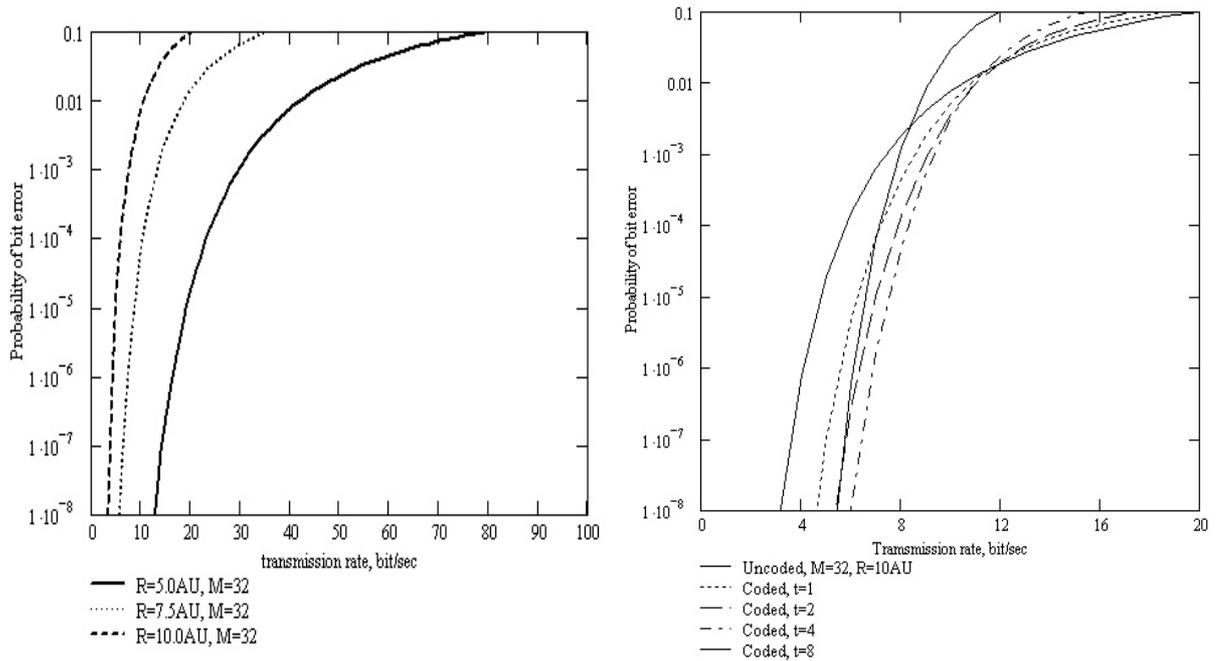
Figure 5: **Left panel (a):** Incoherent MFSK, the bit error rate as a function of the transmission rate; the transmitter power $P_{\text{tr}} = 1$ W, $M = 32$, the distance is a parameter; **Right panel (b):** Incoherent MFSK with the same parameters; the distance $R = 10$ AU and preliminary Reed-Solomon coding, the parameter t is the number of symbol errors guaranteed to be corrected by the code.

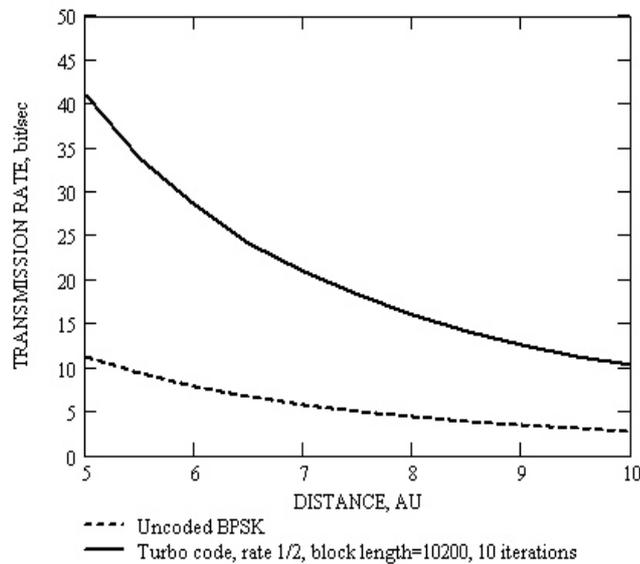Figure 6: The transmission rate as a function of the distance; $P_{\text{tr}} = 1$ W, $BER = 10^{-5}$. Dash line: uncoded BPSK, $SNRbit = 9.59$ dB. Solid line: turbo code, rate 1/2, block length=10200, 10 iterations, $SNRbit = 1.0$ dB.