

IEEE802.15.4 Wireless Sensor Network in Mars exploration scenario

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Abstract—The IEEE 802.15.4 standard (ZigBee) provides low cost and low power connectivity for Wireless Sensor Network (WSN) devices that need a monthly or years duration of battery, with low DataRate and small dimensions. All such features fit pretty well the requirements of a space mission and for this reason the spatial community is investigating the possibility of using WSN in planetary exploration context, in particular on Mars. After an accurate analysis of the past missions retrieved data, we individuate the most common propagation contexts on Mars and we evaluate the performance of an IEEE802.15.4 standard based sensor network working at 2.4GHz for that contexts. In order to evaluate the applicability of the IEEE 802.15.4 standard to planetary exploration context, a characterization of the most common five frequency channel is obtained taking into account all the Martian geomorphologic, atmospheric and eolian features. Considering such frequency channels, thanks to Simulink and OMNET++ simulation models, network performances like Bit Error Rate (BER), Symbol Error Rate (SER) and Throughput are obtained. The possibility to implement a packet level coding is also investigated.

I. INTRODUCTION

It was the February 6th, 2004 when the ESA board of directors declared that "Beagle 2" got lost. The failure of the Mars Express mission showed the inherent hazard using a single centralized system in planetary exploration context. For this reason the spatial community has focused the attention on alternative solutions, like redundant systems, in order to reduce mission failure risks. Among the possible solution, the utilization of Wireless Sensor Network (WSN) represents a optimal candidate. The interest for wireless communication in space missions have been growing-up in the last years, driven on one side by the complexity on new space systems and supported by the technological trend for ground commercial utilization, that makes available standards and products based on RF. Potential space applications for RF wireless systems are numerous, like planetary surface exploration, intra-satellite devices communication, extra-vehicular operations.

Born as data networks for personal areas (WPAN), WSN have rapidly gained a growing importance in many other contexts. The IEEE 802.15.4 standard (ZigBee) provides low cost and low power connectivity for WSN devices that need a monthly or years duration of battery, with low DataRate and small dimensions. One of the most interesting and innovative field of application of WSN is represented by the planetary exploration context; the aim of this paper is to present the

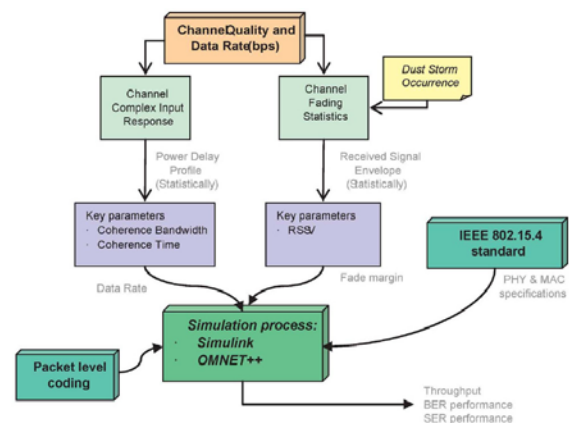


Fig. 1. Block diagram showing the analysis process used to obtain WSN performance in planetary exploration context

performance evaluation of an IEEE802.15.4 standard based network in Mars exploration context.

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II. PROPOSED APPROACH

A block diagram view of the logical process of analysis used to investigate the ZigBee usability in planetary exploration context is shown in Fig. 1; in such analysis we consider a set of five possible scenarios, referring to realistic scenarios of Mars. Therefore, thanks also to the recent information given by Phoenix Mission, in this paper different Martian radio frequency channel models are studied; such models take into account all Martian features, like Tropospheric effects, clouds, wind, snow, gaseous attenuation and dust storm effect. Given the specific characteristic of the network, a particular attention will be focused on the signal degradations caused by the occurrence of dust storms with different intensities. The knowledge about such channels allow to investigate system transmission and network performance, thanks to simulation process with Simulink and OMNET++. We also investigate the possibility to implement a packet level coding.

III. MARTIAN FREQUENCY CHANNEL CHARACTERIZATION

In order to obtain the performance of a WSN in planetary exploration scenario of Mars, we need to take into account several features affecting the propagation of radio wave. The principals are: presence of clouds, snowfalls, temperatures, gaseous composition of the Martian atmosphere (different from the Earth's one), presence of obstacles (rocks and craters) and possible occurrence of dust-storms. Among them, last two features offer the major contributions to the radio wave attenuation and, furthermore, such contributions vary according to Martian region of interest and time of the year. These aspects should be considered during the planning of the space mission.

A. Rock-Density dependent Channels

Different rock distributions (in terms of density and dimension) can be present on the Martian soil, as we can observe in Fig. 2; for this reason we consider two different channel modes related to two different surface morphology scenarios:

- "Normal" channel
(Low-Medium rock density and dimension),
- "Rocky" channel
(High rock density and dimension).

In particular, considering the possible wave-propagation paths (LOS and NLOS) and the multipath components, "Normal" channel can be described statistically as a Ricean channel, with a Rice Factor $k = 10$ (ratio between LOS and NLOS component power) and a probability density function given by [1]:

$$p(E) = \frac{E}{\sigma^2} e^{\frac{E^2 + A^2}{2\sigma^2}} I_0\left(\frac{EA}{\sigma^2}\right) \quad (1)$$

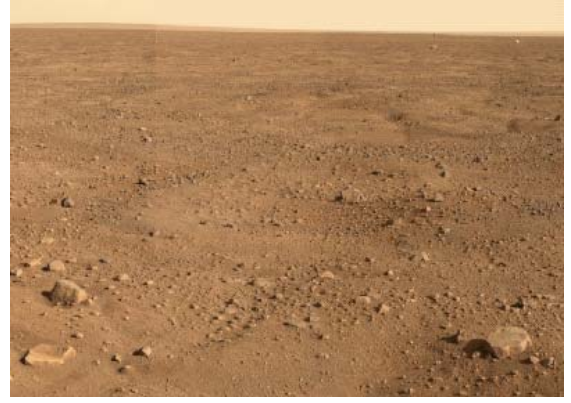
where the parameter A denotes the peak amplitude of the dominant signal, $I_0(\cdot)$ is the modified Bessel function of the first kind and zero-order, σ^2 is the time-average power of the received signal.

"Rocky" terrain scenario is characterized thanks to the frequency distributions obtained from data collected by Viking 1 and 2 landers; such distributions give information about dimensions and number of rocks per m^2 of Martian rocky landing sites. Taking into account such information and comparing sensors and rocks dimensions, "Rocky" channel can be described statistically as a Rayleigh channel, with a probability density function given by:

$$p(E) = \frac{E}{\sigma^2} e^{-\frac{E}{2\sigma^2}}, \quad E \geq 0 \quad (2)$$

B. Dust-Stormy Channels

One of the most remarkable features of Mars is the dust storm. Thus, there are some concerns about dust storm effects on radio wave propagation. Obviously, many consideration need to be mentioned; here we report the main features of interest. For a detailed description of the argument, please refer to [2]. Dust-storms occur primarily in the south hemisphere of Mars, but sometimes they can cover the whole planet. Since they differ in dust particle density (from $N_T = 1 \times 10^7 m^{-3}$ to



(a) Low rock density region



(b) High rock density region

Fig. 2. Two picture of different rock density regions of Mars, made by "Phoenix" and "Viking 1" landers.

$N_T = 8 \times 10^7 m^{-3}$) [2] and wind strength (from 2 to 28m/s), we consider three different channel models, identifying the most common situations:

- "Faint Dust-Storm" channel
(Low particle density, faint wind, $\bar{r}=1\mu m$)
- "Strong Dust-Storm" channel
(Medium particle density, strong wind, $\bar{r}=10\mu m$)
- "Heavy Dust-Storm" channel
(High particle density, heavy wind, $\bar{r}=20\mu m$)

Goldhirsh [3] and Chu [4] give an expression of the attenuation caused by a Martian sand storm, when a distribution of particle size is available:

$$A(\lambda) = \frac{1.029 \times 10^6 \varepsilon''}{\lambda \left[(\varepsilon' + 2)^2 + \varepsilon''^2 \right]} N_T \bar{r}^3 \quad [\text{dB/km}] \quad (3)$$

where λ is wavelength in meters, N_T is the total particle density in $\#/m^3$, ε' and ε'' are the real and imaginary part of the dielectric permittivity index and \bar{r} is the mean particle radius in meters, obtained through an integration over all sizes of particles in the normalized particle number density $N(r)$ [5]. At the present time there aren't accurate measurement of the mean particle radius, but it can be considered included in

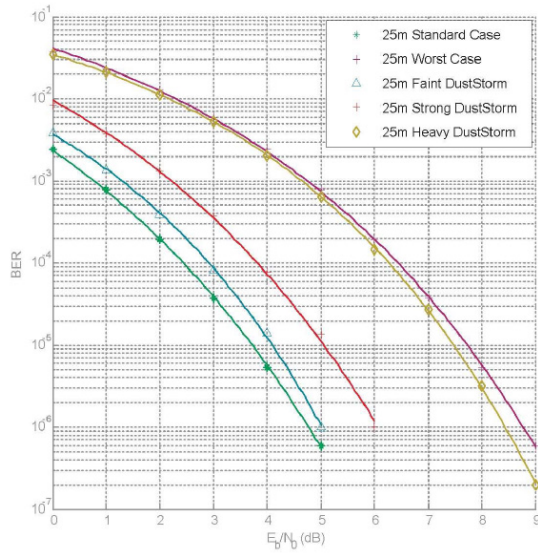


Fig. 3. BER trends comparison for different channels, considering a 25m distance transmission and OQPSK modulation.

[1 μ m; 20 μ m].

C. BER performance

Referring to the above mentioned channels, we obtain the Bit Error Rate (BER) performances of OQPSK modulation (used in IEEE 802.15.4 standard) for different distances of transmission. The results shown in Fig. 3 are obtained simulating the transmission system with a Simulink based model, varying parameters of "Channel" block according to different channel simulation. For "standard Case", "Faint Sandstorm" and "Strong Sandstorm" we can observe good values of BER and, more generally, a progressive degradation of the trends according to the worse conditions of propagation. In case of high density of rocks ("Worst case") and "Heavy Sandstorm", BER trends look very similar and they can be assumed as worst cases among the proposed channel models.

D. SER performance

According to the IEEE 802.15.4 standard for transmission at 2.4GHz, we include in the Simulink model a DSSS spreading technique; each data symbol (4 bit) of the information stream is mapped in a 32-chip PN sequence. The PN sequences are related to each other through cyclic shifts and/or conjugation (i.e., inversion of oddindexed chip values). Thanks to this spreading technique, we can observe a good performance improvement in terms of Symbol Error Rate (SER), as shown in Fig. 4.

IV. PACKET LEVEL CODING EVALUATION

In case of degraded or fading channel, the utilization of packet level coding techniques could appreciably improve the network performance. Taking into account the limited

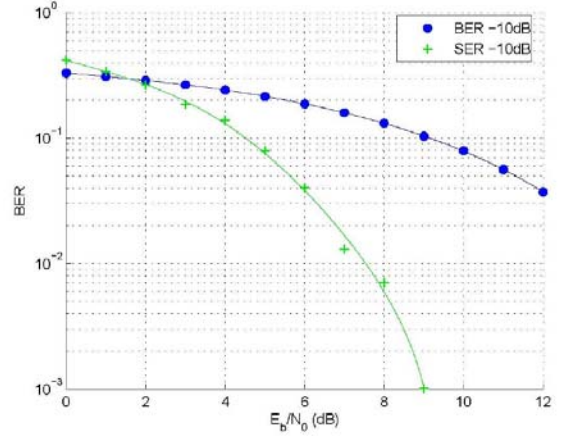


Fig. 4. SER vs. BER trends for a Standard case channel considering a 55m distance transmission.

TABLE I
SOME COEFFICIENTS OF GENERATOR POLYNOMIALS FOR BCH CODES (N,K)

n	k	t
7	4	1
15	11	1
	7	2
	5	3
31	26	1
	21	2
	16	3
	11	5
	6	7

computational capability and the low power consumption requirements for every sensor, we consider the implementation of cyclic Bose-Chaudhuri-Hocquenghem (BCH) coding technique with a limited number of redundant bits. In TABLE I [6] are reported the most suitable BCH-code parameters for the context we are considering. The utilization of transmission coding could be optional: whenever the "link quality indicator" (LQI, see [7]) detects a degradation of the transmission channel characteristics, the WSN coordinator informs the other WSN sensors to switch in encoded transmission mode. Such command could be simply transmitted in the beacon; in this way, retransmission could be quite reduced.

In Fig. 5 are shown the BER performance of a ZigBee network implementing BCH coding technique, for different coding rates. The results are obtained thanks to Simulink simulation processes.

In order to avoid packets of errors that are typical in fading channels, we also consider the use of an interleaving technique, where matrix dimensions depends on the characteristics of the fading channel.

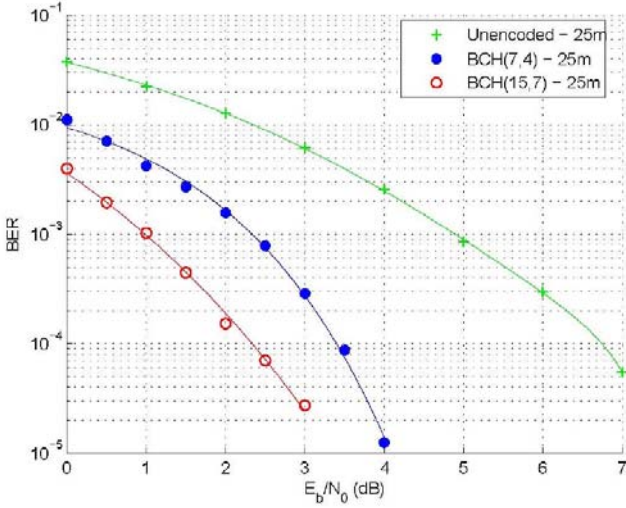


Fig. 5. Comparison among BER trends of unencoded and BCH-coded transmissions for a "Heavy" dust-stormy channel, considering a 25m distance transmission.

V. OMNET++ SIMULATIONS

Thanks to OMNET++, an open source discrete event simulation system, we realized a transmission system of an IEEE 802.15.4 network, formed by a mobile rover and 40 sensors, randomly deployed in a $100m^2$ square area.

A. Used model

Every sensor is defined as a compound element, since the architecture of every sensor is composed by modules (see Fig. 6(a)); "Physic" block is used to create, maintain and delete the transmission links, "MAC" block checks the MAC header of every packet, "AODV" block represent the routing algorithm, "Application" is used to described the type of the collected data (i.e. temperature, pressure, seismic activity, etc), "Battery" block simulate the battery life of the sensor (it decreases for every sent message); used only in rover structure, "Mobility" block defines the direction and the velocity of the rover.

Referring to IEEE 802.15.4 physical specifications [7] for OQPSK modulated transmission at 2.4GHz, we consider an uncoded Bit Error Probability given by:

$$P_e(SNR_{20m,dB}, d) = \frac{1}{2} \operatorname{erfc} \left(\sqrt{[SNR_{20m,dB} + L_{20m,dB} - L(d)_{dB}]_{lin}} \right) \quad (4)$$

where $SNR_{20m,dB}$ is the reference SNR term at the receiver placed at 20 m from the transmitter (in dB), the $[\cdot]_{lin}$ operator represents the linear conversion of the argument, $L_{20m} = L(20)$. The pathloss terms are obtained considering:

$$P_{RX} = \frac{P_{TX}}{L(d)} \quad (5)$$

where

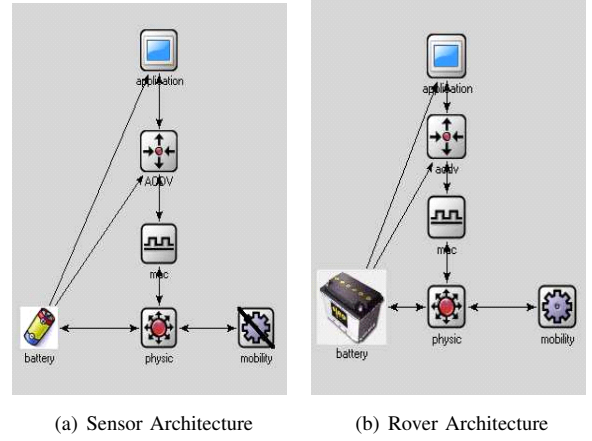


Fig. 6. Sensor (left side) and rover (right side) architecture in OMNET++.

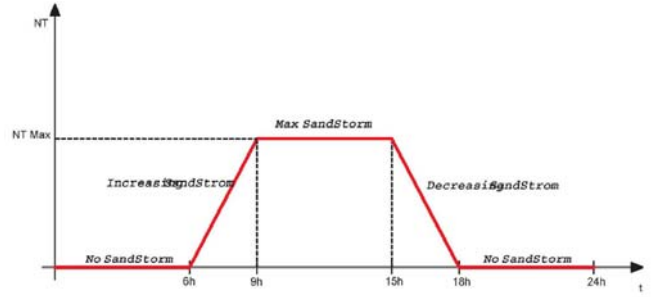


Fig. 7. Simulation time sequence: occurrence of a sandstorm.

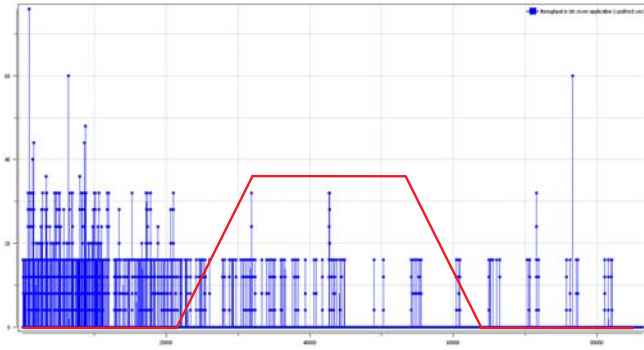
$$L(d) = \left(\frac{4\pi d}{\lambda} \right)^2 \quad (6)$$

Since the reference scenario is a terrain with a medium/high density of rocks, we consider a 3^{rd} order exponent for the Path Loss as experimental approximation for terrains with numerous scatterers. Imposing the Bit Error Probability maximum equals to 4.8×10^{-5} , we obtain that 20 meters transmissions are permitted at least.

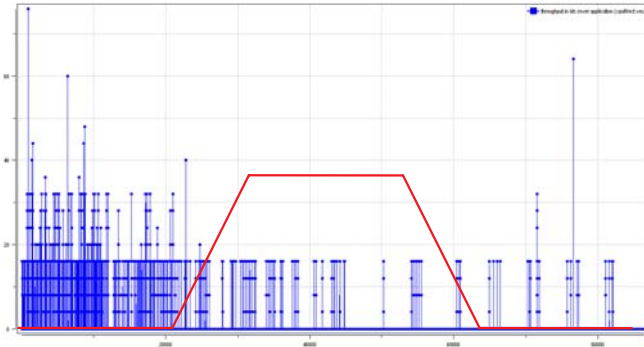
B. Simulation results

In order to evaluate the variation of the network performance during a 24h-transmission, we establish that on time $t=6h$ of the simulation, a 12h-sandstorm occurs, as shown in Fig. 7. The intensity of the sandstorm depends on N_T and the attenuation is calculated with equation 3.

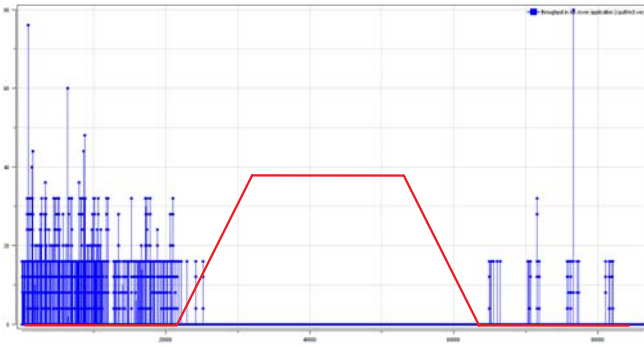
In line with the above mentioned Martian channel in presence of dust storm, we consider three different cases of simulation. Results can be seen in Fig. 8; a clear throughput performance degradation is appreciable, according to the increase of the sandstorm intensity. In case of "Faint" and "Strong" sandstorm throughput performance makes lower, but network still works. Nevertheless for an "Heavy" sandstorm no transmission is possible and network turns off.



(a) "Faint" Sand Storm



(b) "Strong" Sand Storm



(c) "Heavy" Sand Storm

Fig. 8. Throughput measured by the Rover in case of "Faint" Sand Storm, "Strong" Sand Storm, "Heavy" Sand Storm.

VI. CONCLUSION

In this paper we consider the opportunity to use an IEEE 802.15.4 standard based network in Martian planetary exploration context. Thanks to an evaluation of the main features of Mars, we define five different channels that model the five most common propagation contexts. In order to obtain the channel data rate and availability, a capability analysis is performed, considering the power delay profile, the received signal envelope and the measure of channel RF traffic. For the mentioned channels, we evaluate BER and throughput performances of a WSN, performing 24h-long simulation campaigns. Considering a network formed by a mobile rover and

40 sensors, we results obtained from simulations demonstrate that an IEEE802.15.4 based WSN can be used in planetary exploration context. Such WSN works pretty well, also in case of transmission within terrains with high density of rocks. In the case of sand storms occurrence, network performances degrade proportional with the storm intensity and dust particles dimensions. For faint dust storm, WSN works well; in case of heavy dust storm, WSN performances become critical. Nevertheless the WSN is able to react positively after the cessation of the perturbation. The results shown in this paper, demonstrate that WSN should be used in future mission of planetary exploration; a test campaign should follow in order to validate simulated and predicted data.

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