Reliability Analysis of ZigBee Based Intra-Vehicle Wireless Sensor Networks

Md. Arafatur Rahman

Department of Electrical Engineering and Information Technologies (DIETI)
University of Naples Federico II, Naples, Italy
Laboratorio Nazionale di Comunicazioni Multimediali (CNIT), Naples, Italy
`arafatur.rahman@unina.it`

Abstract. Reliability is one of the key issues in intra-vehicle wireless sensor networks, which is a promising research area due to the increasing demand of various safety and convenience applications in the vehicle. Most of the works about this mainly focus on wireless, sensor and computer networks. However, the reliability analysis on intra-vehicle wireless sensor networks is not similar to others because of the complex environment created by a large number of parts inside the vehicle. In this paper, we analyse the reliability for single link between a base station and a sensor node based on ZigBee standard. A robust system design can be achieved by utilizing the experimental analysis.

1 Introduction

The number of sensors in the vehicle has increased significantly due to the various safety and convenience applications. Generally, the Sensor Nodes (SNs) and the microprocessor in a vehicle communicate over a serial data bus are connected with physical wires. The wired architecture is not scalable and flexible due to the internal structure of the vehicle [1]. Therefore, there is an increasing level of appeal to design a system in which the wired connections to the SNs are replaced with wireless links. To this end, the feasibility of different technologies, such as Radio Frequency IDentification (RFID) and ZigBee, has been investigated in [2–5].

Reliability is one of the key issues in Intra-Vehicle Wireless Sensor Networks (IVWSNs). The level of reliability varies with different communication parameters such as distance between Base Station (BS) and SN, transmission power and channel fading. From Fig. 1, we can see that the transmission power of the BS is set P_{t1} if the distance between BS and SN is d_1. When the distance is increased from d_1 to d_2 then the transmit power needs to be increased from P_{t1} to P_{t2} for receiving same level of received signal by the SN. We also notice that due to the increasing of distance between BS and SN, the obstacles may come in the propagation path that changes the line-of-sight (LOS) to non LOS (NLOS). As a result, the fading distribution of a channel will be changed. For achieving the reliability in IVWSNs, the above parameters need to be adjusted.

A. Sikora et al. (Eds.): Nets4Cars/Nets4Trains/Nets4Aircraft 2014, LNCS 8435, pp. 103–112, 2014.

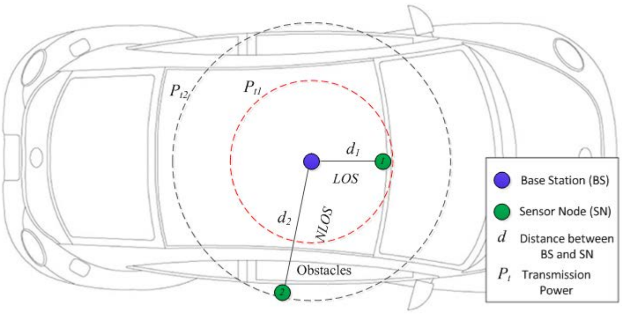

Fig. 1. Communication parameters change the scenario inside the vehicle

In this paper, we analyse the level of link reliability in IVWSNs based on ZigBee standard, with the objective to achieve a robust system design by utilizing the experimental outcomes.

The rest of the paper is organized as follows. In Section 2, we provide the related work, while in Section 3, we describe the theoretical background. In Section 4, we discuss about the reliable link analysis between BS and SN. Finally, in Section. 5, we conclude the paper.

2 Related Works

Most of the works about reliability analysis mainly focus on wireless, sensor and computer networks [8–15]. However, few works have addressed particularly the link reliability in Intra-Vehicle Wireless Sensor Networks [1, 5, 7, 16–18]. In [8], the authors present an empirical study based link reliability estimation in wireless networks. In [9], the author proposes an approach which especially overcomes the drawback of Monte Carlo method for only solving reliability problems in large computer networks. In [10], the authors improve the paper [9] and make it suitable for the WSNs. The reliability analysis on intra-vehicle communication is not similar to the aforementioned works due to the the internal structure of the vehicle. In [1], the authors report the statistical characteristics of 4 representative intra-vehicle wireless channels on the basis of the results of received power measurements and verify the level of reliability of the channels. In [5], the authors evaluate the ZigBee standard specially for cyber-physical systems, which is a class of engineered systems that features the integration of computation, communications, and control. Finally, in [7], the authors propose another work to characterize the wireless channel for intra-vehicle wireless communication.

Unlike all the aforementioned works, in this paper we analyse the level of link reliability in IVWSNs and tune the communication parameters based on ZigBee standard. A robust system design can be achieved by utilizing the experimental results.

3 Theoretical Background

This paper analyses the reliability of intra-vehicle wireless sensor networks. In this section, we provide the theoretical background of the work.

The time variations of the received power are usually caused by the changes in the transmission channels due to the fading effects. There are two kinds of fading: i) large-scale fading and ii) small-scale fading.

Large-scale fading includes path losses and shadowing effects. The path loss is generally modeled through empirical evaluations specially for WSN. The expression of path loss can be written as follows [6]:

$$PL(d)[dB] = PL(d_0)[dB] + 10\gamma \log_{10}(\frac{d}{d_0}) + X_\sigma \tag{1}$$

where X_σ is a Gaussian random variable, $\mathcal{N}(0, \sigma^2)$, with zero mean and variance σ^2, also known as log-normal shadowing, $PL(d_0)$ is the path loss in dB at the reference distance d_0 and γ is the path loss exponent.

The performance of this model not only depends on the distance between transmitter and receiver, but also the path loss exponent and the variance of the log-normal shadowing.

On the other hand, small-scale fading is caused by the interference between multiple versions of the transmitted signal, which arrive at the receiver at slightly different times. Three different propagation mechanisms can happen between the antennas of the transmitter and receiver in the vehicle such as reflection, diffraction and scattering [1]. Reflection occurs when the signal impinges on objects whose dimensions are larger than λ (signal wavelength). Diffraction occurs when the signal impinges on objects with sharp edges. Scattering occurs when the signal impinges on several objects whose dimensions are smaller than or comparable to λ.

The fading distributions of wireless channels can be characterized into two distribution functions, such as Ricean and Rayleigh distributions. The Ricean distribution occurs when there is a presence of dominant stationary signal component, such as a line-of-sight propagation path. In this case, the random multipath components arriving at different angles are superimposed on a stationary dominant signal. Because of the large number of multipath components, central limit theorem can be applied and the sum of these random components can be approximated by the Gaussian distribution. The Ricean distribution is given by:

$$p(r) = \frac{r}{\sigma^2} e^{-\frac{r^2+A^2}{2\sigma^2}} I_0(\frac{Ar}{\sigma^2}) \tag{2}$$

where r is the received signal amplitude, A is the peak amplitude of the stationary dominant signal, and $I_0(.)$ is the modified Bessel function of the first kind and zero-order.

On the other hand, the Rayleigh distribution occurs, when the dominant signal becomes weaker and comparable to other random multipath components. The Rayleigh distribution is given by:

$$p(r) = \frac{r}{\sigma^2} e^{-\frac{r^2}{2\sigma^2}} \tag{3}$$

The Ricean distribution can be described in terms of a parameter K which is defined as the ratio between the deterministic signal power and the variance of the multipath and is given by [1]:

$$K[dB] = 10\log(\frac{A^2}{2\sigma^2}) \tag{4}$$

The Rayleigh distribution can be considered as a special case of the Ricean distribution with $K = -\infty$.

It could expect that the intra-vehicle wireless channels with strong LOS signals to follow the Ricean distributions while the others NLOS signals to follow the Rayleigh distributions. However, these conventional ideas may not work properly, due to the complex environment created by a large number of parts inside the vehicle. Consequently, the actual distributions need to be obtained by analyzing the experimental data, as discussed in [1, 7].

In this paper, we analyse the level of link reliability in intra-vehicle wireless sensor networks with the varying of communication parameters, which are suitable for IVWSNs. The reliability for single link is defined as follows:

Definition 1 (Reliability for single Link). *The level of reliability for single link between a BS and a SN depends on the function of Throughput, Packet Loss Ratio (PLR) and Valid Packet (VP).*

where the parameters of the function are defined as follows:

Definition 2 (Throughput). *Throughput is the total data traffic (bits/s) successfully delivered to the 802.15.4 MAC layer of the receiver and sent to the higher levels.*

Definition 3 (Packet Loss Ratio). *Packet Loss Ratio (PLR) is the ratio of Dropped Packets (DPs), i.e., packets that are affected by a number of bit errors and can not be corrected by the Cyclic Redundancy Check (CRC), and Arrived Packets (APs), i.e., packets arriving at the BS with a power greater than the receiver sensitivity.*

Definition 4 (Valid Packet). *Valid Packet (VP) is the percentage of packets that arrive at the receiver with power greater than the receiver sensitivity.*

4 Reliable Link Analysis between BS and SN

In this section, we study about the communication reliability on single link between BS and SN, since the design of a IVWSNs can not be separated from the study on the link between the different sensor nodes distributed in the vehicle. In order to do that, we have carried out a series of simulations through a discrete event simulation software, OPNET, with the relative packages for the ZigBee module.

4.1 Scenario

A pair of transmitter (i.e., SN) and receiver (i.e., BS) communicates each other within a vehicle. The BS collects the packets that are transmitting periodically by the SN. The BS and the SN are placed at a distance d.

4.2 Communication Parameters

The following are the communication parameters that are used for the experiments.

- Transmit Power set: {-10, -15, -20, -25} dBm, which is suitable for ZigBee, such as the Crossbow MICAz MPR2400 [19];
- Carrier frequency: 2.4 GHz (ISM band), which is used on ZigBee sensor node;
- Receiver sensitivity: The reception threshold of the BS is set equal to -95 dBm, typical for ZigBee [19];
- Distance between BS and SN: 1 to 6 meters (with intervals of 1 meter), which will cover the entire length (or more) of a passenger car;
- Transmission Period: 10 ms;
- Channel: The channels 1 (a, b) are for NLOS paths with Rayleigh fading. The channels 2 (a, b) are for LOS paths with Rice fading and the value of the parameter K is 20.16 dB and 16.08 dB, respectively. The path loss exponent γ for channel 1(a) and 2(a) is 3 and for channel 1(b) and 2(b) is 4. The values of shadowing deviation $\sigma[dB]$ is 8. These values are suitable for intra-vehicle wireless sensor networks [1, 7].
- Packet size: 220 bits (ZigBee packet header 120 bits + data 100 bits);
- Parameters MAC: Retransmissions have been disabled in order to focus on the quality of the connection;

4.3 Experimental Results

In this subsection, we discuss the reliability analysis between BS and SN in terms of throughput, Packet Loss Ratio (PLR) and Valid Packet (VP), as described in Definition 1-4.

In terms of throughput, we analyse how the average throughput behaves with the variation of distance between BS and SN, transmission power, and also the effect of Rice and Rayleigh fading.

Fig. 2 shows the behavior of the average throughput with the variation of distance between BS and SN for Channel 1 (a, b). The figure clearly shows a decreasing trend of the average throughput with increasing distance. The cause of this trend is due to the low power level of the packets arriving to the antenna of BS. Indeed, from (1) we know that the path loss increases with distance and the effect of the log-normal shadowing involves a fluctuation in time of the received power, which can further degrade the performance of the communication. These fluctuations may lead the level of received power below the receiver sensitivity (-95 dBm). Then, the BS evaluates the received packet as noise and consequently, the packet is lost.

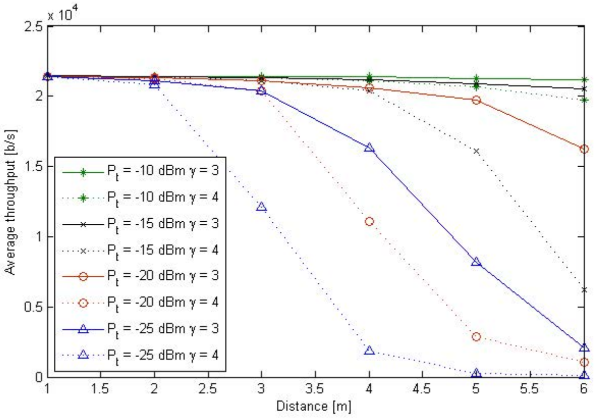

Fig. 2. Comparison of the average throughput experienced by the Channel 1 (a, b)

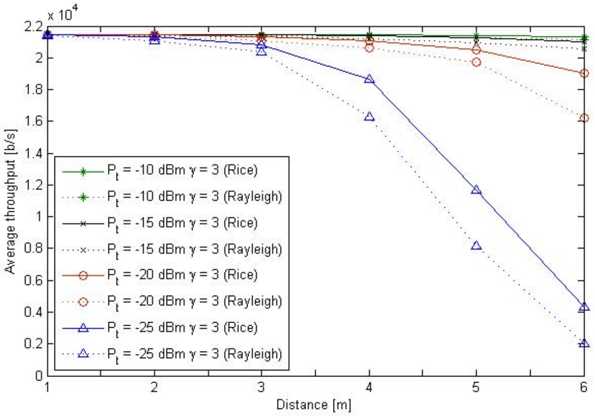

Fig. 3. Comparison of the average throughput experienced by the channel 1(a) and 2(a)

In Fig. 3, it shows the comparison of the average throughput experienced by the channel 1(a) (Rayleigh fading) and 2(a) (Rice fading). From the figure, we see that, as expected, the channel 2 (a) is the favorable case because of the presence of dominant signal component in Rice fading. We also (as similar in Fig. 2) note that a dramatic decrease of average throughput when the distance between BS and SN passes from 4 to 5 meters, in the case of Rice fading with -25 dBm, it is about 12 Kb/s, while in the case of Rayleigh fading, it is about 8 Kb/s. This trend is due to the decreasing of received power below the receiver sensitivity.

In terms of PLR, we analyse how the PLR behaves with the variation of distance between BS and SN, and transmission power, as shown in Fig. 4. The PLR increases with the increasing of distance between BS and SN. As the distance increases, the power level at which packets are received by the BS decreases, and

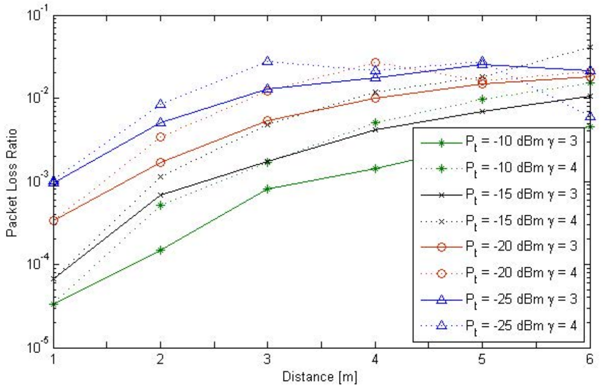

Fig. 4. Packet loss ratio versus distance between BS and SN

consequently, it decreases the SNR. This causes the increasing of the BER that may discard the packets. We note that, for low values of the transmission power, for example $P_t = -25\ dBm$ with $\gamma = 4$, and $P_t = -20\ dBm$ with $\gamma = 4$, seem to improve the performance, as in Fig. 4 one can observe a decrease of PLR. In fact, this trend is not for the improvement of performance, but the fact is the number of packets arriving at the BS, with a low power than the receiver sensitivity, increases to this point that distorts the performance, as the PLR is calculated from the packets arriving at reception with a power greater than the receiver sensitivity. In the case of Rice fading, the PLR can be considered equal to zero, since the performance in terms of Bit Error Rate (BER) are very good so that there is no packet discarded after the error control check CRC.

In terms of VP, we analyse how the VP behaves with the variation of distance between BS and SN, transmission power, and also the effect of Rice and Rayleigh fading.

Fig. 5 shows the percentage of valid packets for channel 1 (a, b), the function of the distance between BS and SN, and for different transmission power. As expected, the figure shows a decreasing trend with the distance, Similar to Fig. 2, the cause of this trend is due to the low power level of the packets arriving to the antenna of BS.

In Fig. 6, it is shown the comparison of valid packets experienced by the channel 1(a) (Rayleigh fading) and 2(a) (Rice fading). Similarly in Fig. 3, the channel is affected by Rayleigh fading provides the worst performance with respect to Rice fading. The difference of the valid packets in two cases is more noticed by increasing the distance between BS and SN; in fact, within 3 meters of distance the performance are almost same. This trend can be explained by considering that multipath effects are as more as the difference between the propagation paths; obviously, the less is the distance between transmitter and receiver, the less will be the propagation paths and the distance between them will be decreased.

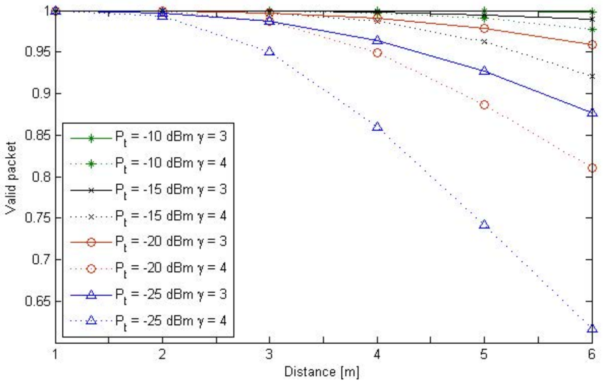

Fig. 5. Comparison of valid packets experienced by the Channel 1 (a, b)

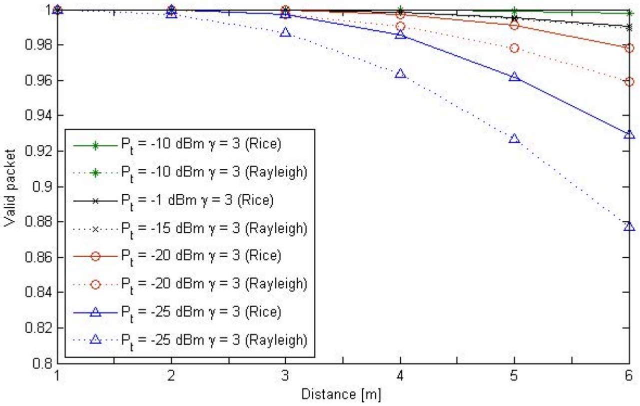

Fig. 6. Comparison of valid packets experienced by the channel 1(a) and 2(a)

From the above analysis, it can be concluded that the BS should be placed in the center of the vehicle specially for the less transmission power. In the hostile scenario (where fading = Rayleigh, $\gamma = 4$, $\sigma = 8$ dB, $P_t = -25$dBm, distance between BS and SN = 2m), the level of reliability is: 97% of the maximum achievable throughput, PLR $< 10^{-2}$ and 99% of VP. In the less hostile scenario (where fading = Rice, $\gamma = 3$, $\sigma = 8$ dB, $P_t = -25$dBm, distance between BS and SN = 3m) the level of reliability is: 97.2.3% of the maximum achievable throughput, PLR is zero and 99% of VP. In the considered scenario (where fading = Rayleigh/Race, $\gamma = 3/\ 4$, $\sigma = 8$ dB, $P_t = -15$ dBm, distance between BS and SN $< 4m$) the level of reliability is: 98.5% of the maximum achievable throughput, PLR is 1.2 x 10^2 and 99% of VP. Indeed, the performance will be more better while the power will increase, however the life time of the SN will be reduced. In the future work, we will investigate the performance by introducing the concept of cognitive radio in intra-vehicle wireless sensor networks [20–23].

5 Conclusion

In this paper, we analyse the reliability for single link between a BS and a SN based on Zigbee standard. Furthermore, we study the hostile and less hostile scenario for analyzing the link reliability. Finally, we consider the suitable scenario for reliable link in the intra-vehicle wireless sensor networks. A robust system design can be achieved by utilizing this experimental analysis. In the future work, we will investigate the performance by introducing the concept of cognitive radio in intra-vehicle wireless sensor networks.

Acknowledgments. This work is partially supported by the project "Mobile Continuos Connected Comprehensive Care (MC3CARE), "DRIVEr monitoring: technologies, methodologies, and IN-vehicle INnovative systems for a safe and ecocompatible driving (DRIVE IN^2)" founded by the Italian national program Piano Operativo Nazionale Ricerca e Competitivit 2007-2013 and the project, "Sviluppo di Tecniche di Comunicazione di Sistemi Embedded Distribuiti" founded by POR Campania FSE 2007/2013.

References

1. Tsai, H.M., Viriyasitavat, W., Tonguz, O.K., Saraydar, C., Talty, T., Macdonald, A.: Feasibility of In-car Wireless Sensor Networks: A Statistical Evaluation. In: Proc. IEEE SECON, pp. 101–111 (2007)
2. Tonguz, O.K., Tsai, H.M., Saraydar, C., Talty, T., Macdonald, A.: Intra-car wireless sensor networks using RFID: Opportunities and challenges. In: Proc. INFOCOM MOVE Workshop, pp. 43–48 (2007)
3. Tsai, H.M., Tonguz, O.K., Saraydar, C., Talty, T., Ames, M., Macdonald, A.: Zigbee-based intra-car wireless sensor networks: A case study. IEEE Wireless Commun. 14, 67–77 (2007)
4. Niu, W., Li, J., Liu, S., Talty, T.: Intra-vehicle ultra-wideband communication testbed. In: Proc. MILCOM, pp. 1–6 (2007)
5. Xia, F., Vinel, A., Gao, R., Wang, L., Qiu, T.: Evaluating IEEE 802.15.4 for Cyber-Physical Systems. EURASIP Journal on Wireless Communications and Networking (2011)
6. Akyildiz, I.F., Vuran, M.C.: Wireless Sensor Networks. Wiley (2010)
7. Moghimi, A.R., Tsai, H.M., Saraydar, C.U., Tonguz, O.K.: Characterizing IntraCar Wireless Channels. IEEE Transactions on Vehicular Technology 58, 5299–5305 (2009)
8. Woo, S., Kim, H.: Estimating Link Reliability in Wireless Networks: An Empirical Study and Interference Modeling. In: Proc. INFOCOM, pp. 1–5 (2010)
9. Shpungin, Y.: Network with Unreliable Nodes and Edges: Monte Carlo Lifetime Estimation. International Journal of Applied Mathematics and Computer Sciences 4, 168–173 (2007)

10. Jin, Y.L., Lin, H.J., Zhang, Z.M., Zhang, Z., Zhang, X.Y.: Estimating the Reliability and Lifetime of Wireless Sensor Network. In: Proc. 4th International Conference on Wireless Communications, Networking and Mobile Computing (WiCOM), pp. 1–4 (2008)
11. Xing, B., Mehrotra, S., Venkatasubramanian, N.: RADcast: Enabling reliability guarantees for content dissemination in ad hoc networks. In: Proc. IEEE INFOCOM, pp. 1998–2006 (2009)
12. Cacciapuoti, A.S., Calabrese, F., Caleffi, M., Di Lorenzo, G., Paura, L.: Human-mobility enabled wireless networks for emergency communications during special events. Elsevier Pervasive and Mobile Computing 9, 472–483 (2013)
13. Cacciapuoti, A.S., Calabrese, F., Caleffi, M., Di Lorenzo, G., Paura, L.: Human-mobility enabled networks in urban environments: Is there any (mobile wireless) small world out there? Elsevier Ad Hoc Networks 10, 1520–1531 (2012)
14. Caleffi, M., Paura, L.: M-DART: Multi-path Dynamic Address RouTing. Wireless Communications and Mobile Computing 11, 392–409 (2011)
15. Cacciapuoti, A.S., Caleffi, M., Paura, L.: A theoretical model for opportunistic routing in ad hoc networks. In: Proc. of IEEE SASN 2009: The International Workshop on Scalable Ad hoc and Sensor Networks, S. Petersburg (RU), October 11-12 (2009)
16. Ma, X., Zhang, J., Yin, X., Trivedi, K.S.: Design and Analysis of a Robust Broadcast Scheme for VANET Safety-Related Services. IEEE Transactions on Vehicular Technology 61, 46–61 (2012)
17. Xu, Q., Mak, T., Sengupta, R.: Vehicle-to-vehicle safety messaging in DSRC. In: Proc. ACM Int. Workshop VANET, Philadelphia, PA, pp. 19–28 (2004)
18. Xing, B., Mehrotra, S., Venkatasubramanian, N.: RADcast: Enabling reliability guarantees for content dissemination in ad hoc networks. In: Proc. IEEE INFOCOM, pp. 1998–2006 (2009)
19. MPR/MIB mote hardware users manual, `http://www.xbow.com`
20. Cacciapuoti, A.S., Caleffi, M., Paura, L., Savoia, R.: Decision Maker Approaches for Cooperative Spectrum Sensing: Participate or Not Participate in Sensing? IEEE Transactions on Wireless Communications 12, 2445–2457 (2013)
21. Rahman, M.A., Caleffi, M., Paura, L.: Joint path and spectrum diversity in cognitive radio ad-hoc networks. EURASIP Journal on Wireless Communications and Networking (2012)
22. Cacciapuoti, A.S., Calcagno, C., Caleffi, M., Paura, L.: CAODV: Routing in Mobile Ad-hoc Cognitive Radio Networks. In: Proc. of IEEE IFIP Wireless Days 2010, Venice, Italy, October 20-22 (2010)
23. Cacciapuoti, A.S., Akyildiz, I.F., Paura, L.: Optimal Primary-User Mobility Aware Spectrum Sensing Design for Cognitive Radio Networks. To Appear in IEEE Journal on Selected Areas in Communications (JSAC)-Cognitive Radio Series (2013)