Technical Report:

“L-CSMA: A MAC Protocol for Multi-Hop Linear Wireless (Sensor) Networks”

C. Buratti and R. Verdone

I. INTRODUCTION

This technical report includes some in depth analysis and extensions of the work presented in [1]. In particular, the reference paper considers a multi-hop wireless linear network, where multiple nodes are evenly spaced over a straight line. Two scenarios are addressed: a network where only one source generates traffic to be transmitted via multiple hops to the destination, and the case of linear sensor networks, where all nodes in the line generate data. A novel contention-based Medium Access Control (MAC) protocol, L-CSMA, is proposed, which is specifically devised for linear topologies. CSMA (Carrier Sensing Multiple Access) suffers from the well known hidden/exposed node problems; the scope of L-CSMA is to reduce their impact, while minimizing the protocol overhead, taking advantage of the knowledge of the number of nodes in the line. L-CSMA assigns different levels of priority to nodes, depending on their positions in the line: nodes closer to destination have higher priority when accessing the channel. The priority is managed by assigning to nodes different durations of the carrier sensing phase. This mechanism speeds up the transmission of packets which are already in the path, making the transmission flow more efficient. Results show that L-CSMA outperforms existing contention-based MAC protocols. A mathematical model to derive the performance in terms of packet success probability and throughput is provided. The latter is validated through comparison with simulations.

This report presents: i) a simplified model for the 5-hop network case; ii) a validation of the proprietary simulator used in [1] through comparison with experimental results and results achieved with NS-3 network simulator; iii) some in depth analysis on capture effect and on the comparison between L-CSMA and the Ripple protocol presented in [10].

II. SIMPLIFIED MODEL FOR THE 5-HOP CASE

A simplified model for the 5-hop case is presented in this section. We refer to [1] for the notations and for the precise analysis.

We evaluated the states probability values for the set of parameters considered in this paper, that are $\alpha = 5$ dB, $P_{R_{min}} = -90$ dBm and $P_{R_{min}}$ in the range (-105,-95) dBm. We discovered that in all cases the states probabilities, $\pi_{\mathbf{O}^{(5)}}$, $\pi_{\mathbf{R}^{(5)}}$, $\pi_{\mathbf{S}^{(5)}}$, $\pi_{\mathbf{T}^{(5)}}$, $\pi_{\mathbf{U}^{(5)}}$, $\pi_{\mathbf{V}^{(5)}}$ were all lower than 0.01. By eliminating the above states from the state transition diagram, we can obtain the diagram presented in Fig. 1.

The simplified matrix of the states transition probabilities, $\mathbf{P}^{(5)}$, is given by:

$$\mathbf{P}^{(5)} = \begin{bmatrix}
0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & \bar{c}_{13}\bar{c}_{31} & 1 & 0 & 0 & \bar{c}_{14} & 0 \\
1 & 0 & 0 & 0 & c_{02}\bar{c}_{20} & 0 & c_{03}\bar{c}_{30} & 0 & 0 & 0 & c_{04} & \bar{c}_{24} & 0 & 1 \\
0 & h_{02} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & h_{02}\bar{c}_{14} & 0 \\
0 & 0 & 0 & 0 & \bar{c}_{02}\bar{c}_{20} & 0 & \bar{c}_{03}\bar{c}_{30} & 0 & 0 & 0 & \bar{c}_{04} & 0 & 0 & 0 \\
0 & \bar{h}_{02} & 0 & 0 & 0 & 0 & 0 & 0 & c_{13}\bar{c}_{31} & 0 & 0 & 0 & \bar{h}_{02}\bar{c}_{14} & 0 \\
0 & 0 & h_{03} & 0 & \bar{c}_{02}c_{20} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & \bar{h}_{03} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & h_{13}c_{02}c_{20} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & \bar{h}_{13}c_{02}c_{20} & 0 & 0 & 0 & 0 & 0 & 0 & c_{24} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & h_{04} & \bar{c}_{03}c_{30} & 0 & h_{04}\bar{c}_{13}c_{31} & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & \bar{h}_{04} & 0 & 0 & \bar{h}_{04}\bar{c}_{13}c_{31} & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & c_{13}c_{31} & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & \bar{h}_{14}c_{03}c_{30} & \bar{h}_{14} & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & h_{14}c_{03}c_{30} & h_{14} & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix} \tag{1}$$

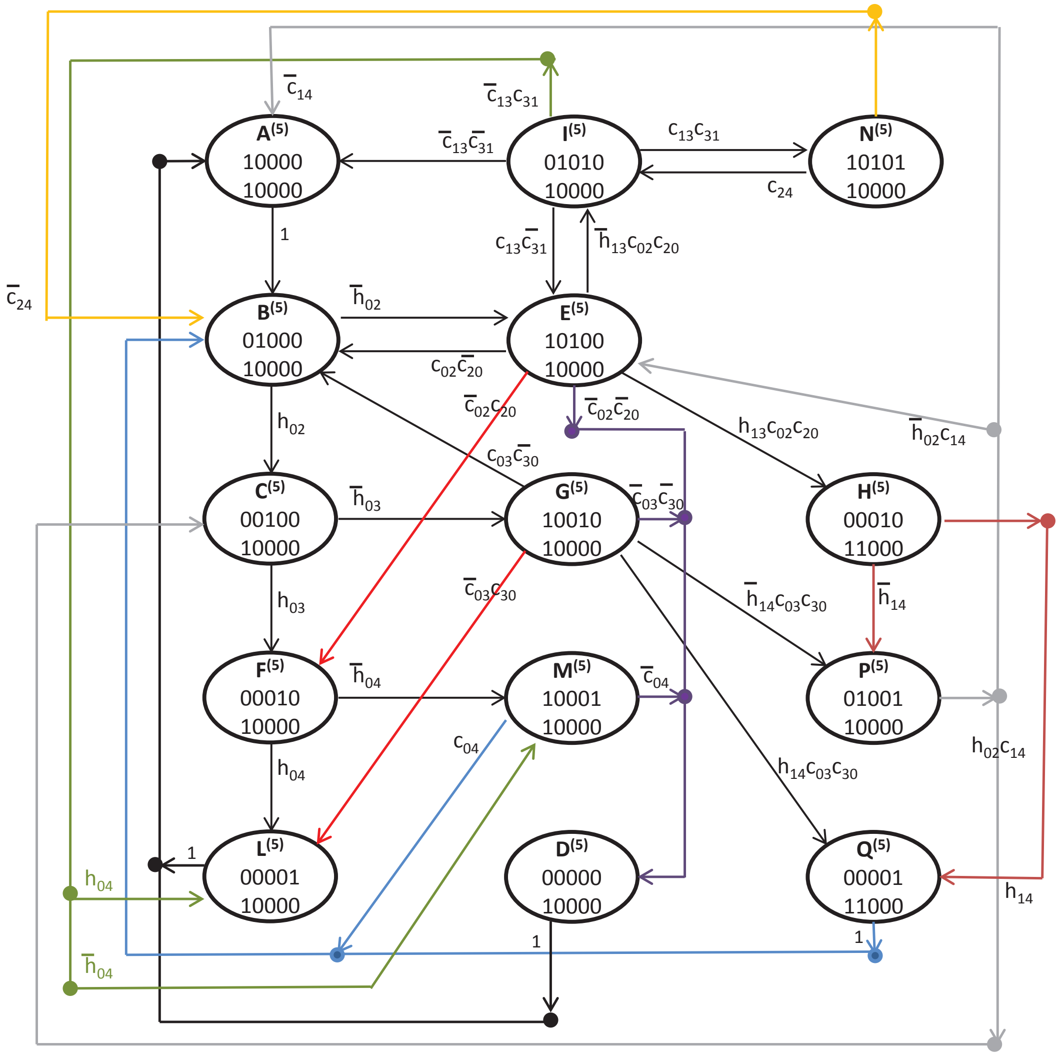

Fig. 1. The state transition diagram for the 5-hop case: simplified analysis.

The generic performance metric (representing $\hat{\Sigma}$, $\bar{p}_S$ and p_S) is given by:

$$
\begin{aligned}
M &= h_{02}\{h_{03}[\beta_1 \cdot h_{04} + \bar{h}_{04}c_{40}(\beta_2 \cdot c_{04} + \beta_3 \cdot \bar{c}_{04})] + \bar{h}_{03}[c_{03}c_{30}(\beta_4 \cdot h_{14} + \bar{h}_{14}c_{41}(\beta_5 \cdot c_{14} + \beta_6 \cdot \bar{c}_{14})) \\
&+ \beta_7 \cdot \bar{c}_{03}c_{30}]\} + \bar{h}_{02}c_{02}c_{20}\{h_{13}[\beta_8 \cdot h_{14} + \bar{h}_{14}c_{41}(\beta_{11} \cdot c_{14} + \beta_{12} \cdot \bar{c}_{14})] + \bar{h}_{13}[c_{13}c_{31}c_{42}(\beta_{13} \cdot c_{24} \\
&+ \beta_{14} \cdot \bar{c}_{24}) + \bar{c}_{13}c_{31}(\beta_{29} \cdot h_{04} + \bar{h}_{04}c_{40}(\beta_{30} \cdot c_{04} + \beta_{31} \cdot \bar{c}_{04})) + \beta_{32} \cdot h_{04}h_{24}c_{13}c_{31}]\} \\
&+ \bar{h}_{02}\bar{c}_{02}c_{20}[\beta_{33} \cdot h_{04} + \bar{h}_{04}c_{40}(\beta_{34} \cdot c_{04} + \beta_{35} \cdot \bar{c}_{04})] \qquad (2)
\end{aligned}
$$

where the values of the parameters β_k for $k = 1, .., 35$ are still those reported in Table II of

TABLE I
RESULTS FOR THE APPROXIMATED 5-HOP MODEL: SIMPLIFIED AND PRECISE MODELS.

$P_{S_{min}}$ [dBm]	Simpl. p_S	p_S	Simpl. $\bar{p}_S$	$\bar{p}_S$	Simpl. Σ	Σ
-105	0.79	0.78	0.88	0.88	7.9	8
-100	0.65	0.64	0.8	0.8	8	8
-95	0.52	0.52	0.73	0.73	7.5	7.5

paper [1].

The results of the simplified model for the 5-hop scenario are given in Table I of this report. In the table results obtained with the simplified model and the precise one (presented in [1]) are compare: as can be seen no significant differences are present, demonstrating that the above approximation is very good.

Finally, we want to underline that even though we were able to derive a simplified model, i.e., a simplified state transition diagram and the corresponding matrix, for the 5-hop case, this is still not sufficient to generalise the model to larger networks. The reason is the following: the state transition matrix for the z-hop case is not included into the state transition matrix of the $z-1$-hop case. The latter is explained in the following example. Let us consider the case of 3 and 4 hops. The columns $\mathbf{P}_j^{(3)}$ with j=1,2 and 4 are, in fact, included in $\mathbf{P}^{(4)}$, while the third column, related to state $\mathbf{C}^{(3)}$ and the last column, related to state $\mathbf{E}^{(3)}$, are different. $\mathbf{C}^{(3)}$, in fact, enters in state $\mathbf{A}^{(3)}$ with probability 1, while $\mathbf{C}^{(4)}$ enters in new states of the chain at 4-hops, that are $\mathbf{F}^{(4)}$ and $\mathbf{G}^{(4)}$ not present in the 3-hop case. Due to the latter, even if we can think about an algorithm to derive the set of state of the z-hop case from the set of states of the the $z-1$-hop case, it is impossible to generalise the derivation of the state transition matrix.

III. VALIDATION OF THE SIMULATOR

Authors in [1] decided to implement a proprietary simulator, instead of using a public network simulator for the following reasons. First of all, there have been some studies in the literature focusing on the accuracy of well known network simulators and some of them have pointed out that there exists significant variations in the way these simulators operate and that their accuracy is not reliable [6], [7]. Also, the validation of some of these simulators through comparison with experimental results not always showed very good performance [8], [9]. Finally, when dealing with mathematical analysis comparison, the accuracy of simulations such as the possibility to fully control all parameter settings are fundamental.

However, to validate the implemented simulator, we compared its results with: i) results achieved through an NS-3 simulator, implementing the 802.15.4 multi-hop protocol using the 802.15.4 model made available by the network simulator; ii) experimental results achieved by using Texas Instruments CC 2530 system on chips[1], being IEEE 802.15.4 standard compliant.

The validation has been done by comparing results for the linear topology when using the IEEE 802.15.4 MAC protocol, however we would underline that the core of the simulators used for the different protocols is the same: same channel model, PHY layer, packet generation function, capture model, routing protocol, performance metrics computation. The only difference stands in the function which is called in order to access the channel, implementing the CSMA/CA backoff algorithm of 802.15.4, slotted aloha or our L-CSMA. Therefore validating the 802.15.4 module of the software is sufficient.

In the experiments we consider a linear network, where the source transmits a burst of 10,000 packets toward the destination, passing through the relays. Relays are programmed such that they forward the received data toward the next hop. Acknowledgement is not used and retransmissions are not allowed. No power control has been implemented at devices, however during the experiments we located devices on a table very near one each other and we set the transmit power to 0 dBm, in order to reduce as much as possible losses due to the physical layer, while ensuring that all nodes in the network could hear each other. In both simulators we used power control (providing no connectivity issues) and we set $P_{\mathrm{S}_{\min}} = -200$ dBm (such that each node can hear each other as in the case of experiments). Note that even though there is no hidden terminal problem, packets can be lost due to: i) two or more nodes can sense the channel at the same time, finding it free and transmitting together; ii) according to the standard a node can try to access the channel for a finite number of times for the transmission of the same packet. In the simulators we also set H=136 bits (17 bytes), and $\alpha = 1.3$ dB. Fig. 2 of this report shows the throughput of the source as a function of the payload size, for experimentations and simulations (both simulators) for the cases of 3 and 4 hops networks. Note that the behaviour of the curves is exactly the same by varying the payload and for the different numbers of hops.

---

[1] See the Texas Instruments web site: http://www.ti.com/product/cc2530.

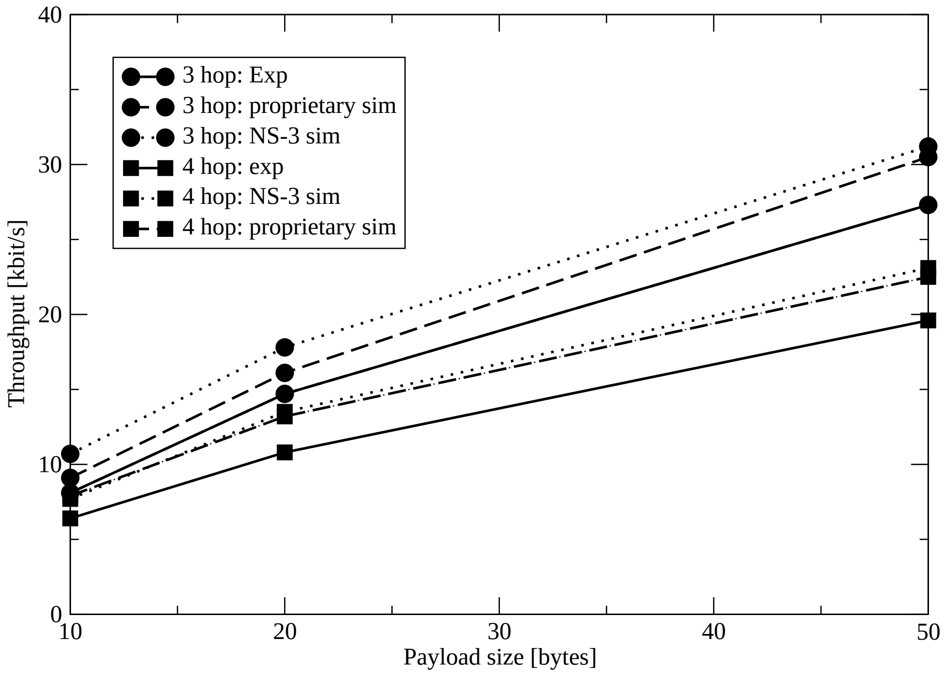

Fig. 2. Throughput [kbit/s], as a function of the payload size when experimentations and the two simulations, the proprietary one and the NS-3 simulator, are considered.

By increasing the number of hops, the processing time at relays causes a decreasing of the throughput and the latter is not accounted for in the simulators. As can be seen the results of the two simulators is almost the same, both are affected by a small error related to the processing time not implemented in the simulators as usual. Both simulators capture the behaviour of PHY and MAC.

IV. NOTES ON CAPTURE EFFECT MODEL

The capture effect, also called co-channel interference tolerance, is the ability of radios to correctly receive a strong signal from one transmitter despite interference from other transmitters. In particular, it is largely assumed in the literature (see, e.g., [2]–[4]), that a signal can be captured if its instantaneous power is larger than the sum of the instantaneous power of other interfering packets by at least a certain minimum threshold factor, also denoted as capture threshold. The latter implies that the probability of detecting the useful signal is a function of the signal-to-interference (SIR) ratio. The latter is the most suitable model and it is the one implemented in the simulator used in [1], used to evaluate the performance of the L-CSMA and to validate the mathematical model. In the mathematical model, instead, we consider a simplified SIR, where, instead of the sum of the interfering powers, we just consider the strongest interference, which is assumed to be the nearest one. The impact of the latter introduced approximation is then checked through comparison with simulations (where all the interferences are accounted for) in Sec. VII-A of [1]: the good fit between simulation and mathematical model results demonstrate that for linear networks the most significant interference always comes from the nearest interference, and the latter is true also in the presence of Rayleigh fading. Finally, we underline that the simplified model considered in the mathematical evaluation is not equivalent to the hop-based interference model considered in the previous work [5]. In the hop-based model, in fact, the useful received power is not considered at all and an interfering node is assumed to be damaging or not depending on its distance from the receiver. However, the latter is not complaint with what happens in real receivers, where, as stated above, the probability of correctly decoding a signal is a function of the ratio between the useful and the interfering power, and not just of the interfering power.

V. COMPARING L-CSMA AND RIPPLE

In [1] the L-CSMA protocol is compared with other protocols, presented in the literature. In particular, among the others, we consider Ripple [10], an interesting novel MAC protocol thought for linear wireless networks, based on a token passing mechanism. The latter is applied to 802.11 CSMA/CA and uses request-to-send (RTS) and clear-to-send (CTS) control packets transmissions, plus the transmission of another control packet, called ready-to-receive (RTR), introduced by the Authors, in order to manage the flow of data in the chain. The latter protocol has been implemented in our simulator and compared to L-CSMA and to the other benchmark solutions. In particular, we have implemented the transmission of three new packets defined in Ripple: RTS, CTS and RTR, used to avoid the hidden terminal problem and acting as tokens. In particular, RTS, sent in downstream (from S to D), triggers the transmission of the next hop; while RTR is sent in upstream (from D to S) and triggers the transmission of the subsequent packet from the previous hop. Since this work is mainly focused on WSNs and, as stated above, it considers 802.15.4 as benchmark solution, the token-passing procedure (using RTS, CTS and RTR transmissions) is applied to the CSMA/CA protocol defined by the 802.15.4 standard, instead of that defined by 802.11. The latter has been done also for fair comparison with respect to 802.15.4, in order to avoid drawing conclusions on differences caused by the different CSMA/CA

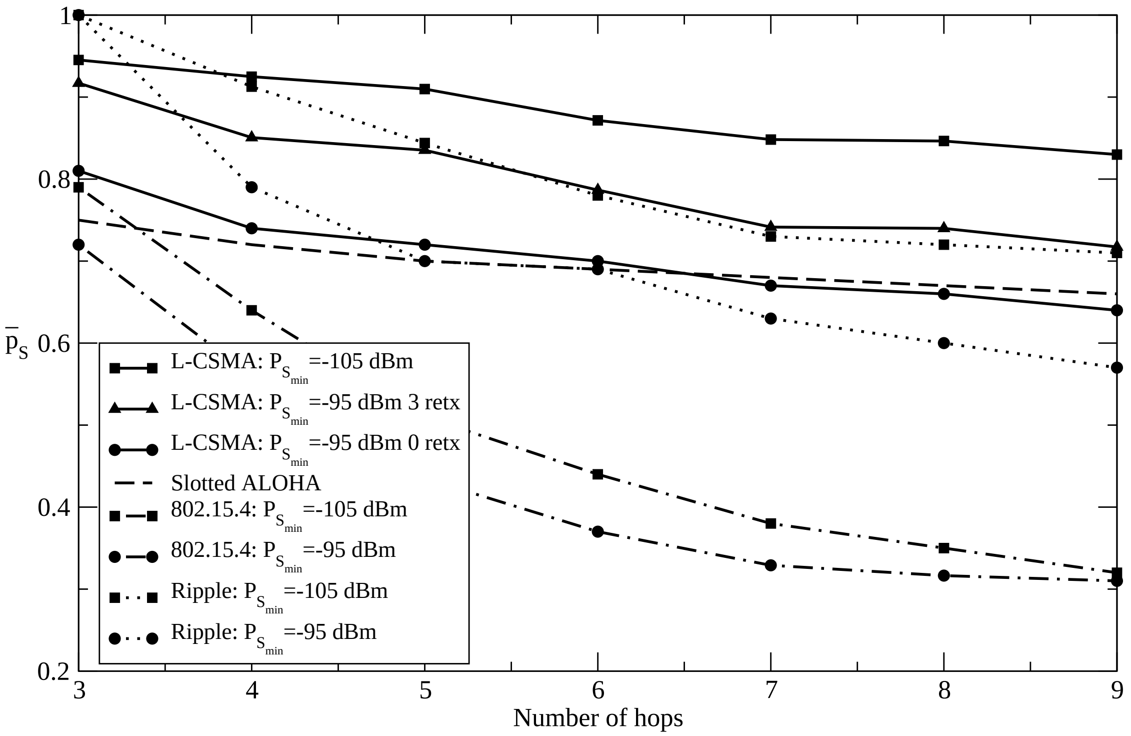

Fig. 3. Average Success Probability among nodes as a function of the number of hops in the case of LWSN.

protocols, rather than the real impact and improvement given by the transmission of the control packets. While Ripple performs well in terms of success probability for a very low number of hops, some losses are present when increasing the network size, since the hidden terminal problem cannot be eliminated due to the presence of random channel fluctuations, and also to possible contemporaneous transmissions. As expected, Ripple performs better than 802.15.4, thanks to the use of RTS/CTS and tokens, but still remains worse than L-CSMA in most of the cases. Finally, in terms of throughput and transmission efficiency the Ripple protocol is the worst among those considered, since it uses three control packets, whose transmission requires time and generates overhead.

Results related to Ripple are shown in the Figs. 9, 11, 12, 13 and 14 of [1]. Only the case of $P_{S_{min}} = -95$ dBm is shown for the sake of readability of the curves, but similar behaviors can be found for the case of $P_{S_{min}} = -105$ dBm. Results related to the average success probability are not included in Fig. 10 of [1], but just commented in the paper, again for the sake of readability. However these results are included in Fig. 3 of this report.

REFERENCES

[1] C. Buratti, R. Verdone, “L-CSMA: A MAC Protocol for Multi-Hop Linear Wireless (Sensor) Networks,” accepted for publication to IEEE Transactions on Vehicular Technologies, 2015.

[2] J.H. Kim and J.K. Lee, Capture effects of wireless CSMA/CA protocols in rayleigh and shadow fading channels, Vehicular Technology, IEEE Transactions on, vol. 48, no. 4, pp. 1277 1286, Jul. 1999.

[3] X. Li and Q.A. Zeng, Performance analysis of the IEEE 802.11 MAC protocol over a WLAN with capture effect, IPSJ Digital Courier, vol. 1, pp. 545551, 2005.

[4] C. Van Der Plas and J.P. Linnartz, Stability of mobile slotted ALOHA network with rayleigh fading, shadowing, and near-far effect, Vehicular Technology, IEEE Transactions on, vol. 39, no. 4, pp. 359 366, Nov. 1990.

[5] C. Buratti and R. Verdone, ”P-CSMA: A Priority-Based CSMA Protocol for Multi-Hop Linear Wireless Networks”, Proc. of IEEE European Wireless (EW), 2013, April 2013.

[6] L. Hogie and P. Bouvry and F. Guinand, ”An Overview of MANETs Simulation”, Electronic Notes in Theoretical Computer Science, Elsevier, pp. 81-101, Feb. 2006.

[7] Daniela De Col, ”Routing protocols for wireless ad-hoc networks: analysis of performance of the AODV and DRS protocols”, Master Thesis, University of Pisa, 2002.

[8] S. Ivanov and A. Herms and G. Lukas, ”Experimental Validation of the ns-2 Wireless Model using Simulation, Emulation, and Real Network”, Proc. of Communication in Distributed Systems (KiVS), 2007, pp. 1-12, Feb. 2007.

[9] M. D. Abrignani and C. Buratti and D. Dardari and N. El Rachkidy and A. Guitton and F. Martelli and A. Stajkic and R. Verdone, ”The EuWIn Testbed for 802.15.4/Zigbee Networks: From the Simulation to the Real World”, Proc. of International Symposium on Wireless Communication Systems (ISWCS), 2013, Aug. 2013.

[10] Ray-Guang Cheng, Cun-Yi Wang, Li-Hung Liao, Jen-Shun Yang, ”Ripple: a wireless token-passing protocol for multi-hop wireless mesh networks”, IEEE Communications Letters, vol. 10, n. 2, pp. 123-125, Feb. 2006.