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Performance Analysis of the RPL Routing Protocol

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***Abstract*—The IETF Routing Over Low-power and Lossy Networks working group has recently proposed the IPv6 Routing Protocol for Low power and Lossy Networks, i.e., the RPL protocol. It has been designed to face the typical requirements of wireless sensor networks. Given its relevance in the industrial and scientific communities, this paper presents a performance analysis of RPL based on simulations. Our results clearly show that RPL can ensure a very fast network set-up, thus allowing the development of advanced monitoring applications also in critical conditions. On the other hand, we found that further research is required to optimize the RPL signaling in order to decrease the protocol overhead.**

***Keywords*—WSN, Routing, Performance evaluation, Simulation, Low-power and Lossy Networks.**

I. Introduction

Wireless Sensor Networks (WSNs) are made by small and cheap nodes with processing, communication and sensing capabilities, that cooperatively interact to carry out complex monitoring tasks in a geographical area of interest [1]. They represent a key technology that will revolutionize the human life in the upcoming years, providing at the same time new business opportunities. Current and envisaged applications will cover many important domains such as: smart-cities, environmental monitoring, distributed sensing in industrial plants, and health care [2].

Usually, in WSN applications, the overall network load is low; nevertheless, such networks poses challenging issues related to the communication reliability and to the efficient use of node batteries [3]. In particular, the routing is a crucial problem in WSNs [4], due to possible link failures, low data rates, and limited energy reserves. In fact, sophisticated techniques are required for setting up and maintaining reliable paths, as well as for promptly detecting link failures, without wasting energy and communication resources [5]. Furthermore, classical routing algorithms devised for ad hoc networks, such as OLSR and AODV, are not able to satisfy the typical requirements of multipoint-to-point WSN applications [6].

This is the main reason why an Internet Engineering Task Force (IETF) working group, namely Routing Over Low-power and Lossy Networks (ROLL) [7], has proposed a novel IPv6 Routing Protocol for Low power and Lossy Networks, that is RPL [8]. As stated in the draft standard [8], RPL is a gradient routing technique [9] that organizes the WSN as a Direct Acyclic Graph (DAG) rooted at the sink. It tries to minimize the cost to reach the sink from any node in the WSN using an objective function. Such a function can be defined in many ways (see the next section for more details), thus obtaining a very high flexibility with respect to the operating scenario.

Given the relevance of RPL for real-world applications, it is important to accurately analyze its performance in multipoint-to-point scenarios, representing the dominant use case [10]-[13]. To this aim, we propose herein a simulation campaign, exploring the efficiency of RPL and the Quality of Service (QoS) it can provide to monitoring applications. In particular, using the Contiki COOJA simulator [14] available at [15], we evaluated, for several WSN sizes and wireless channel reliabilities, the signaling overhead of RPL, the network throughput, and end-to-end packet delays. Results show that RPL is a very powerful routing algorithms because it allows a very fast network set-up and limited delays (below few seconds), but further research is required to understand how to optimize the protocol overhead that can be very high.

The rest of the paper is organized as follows: Sec. II provides an overview on the RPL protocol. Sec. III describes the performance evaluation environment and the simulation methodology. Sec. IV reports and explains simulation results, useful to assess the validity of RPL. Finally, the last Section draws conclusions.

II. RPL Overview

The IETF ROLL working group is going to standardize RPL which is a gradient-based routing protocol for WSNs with bidirectional links. It can support a wide variety of different link layers, including ones that are constrained, potentially lossy, or typically utilized in conjunction with host or router devices with very limited resources [8].

In RPL, given a set of sinks, a DAG (i.e., a gradient) is defined by specifying how link costs and node attributes/status have to be combined in order to compute path costs. Link costs and node information can include available energy resources, workload, throughput, latency, reliability, and so on [16]. In other terms, RPL minimizes the costs to reach any sink (from any sensor) by means of an objective function, which can be defined in many ways to grant for very high flexibility with respect to the operating scenario. Furthermore, RPL strictly adheres to the IPv6 architecture: gradient are set up and maintained using signaling messages carried as options of IPv6 Router Advertisements (RA). In order to be useful in a wide range of LLN application domains, RPL separates packet processing and forwarding from the routing optimization objective.

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RPL splits the DAG into one or more Destination Oriented DAGs (DODAGs), one DODAG per sink. It uses four identifiers to define and maintain a topology:

- *RPLInstanceID*, identifying one of the possible RPL instances running on the same WSN. Each instance may serve different and potentially antagonistic constraints or performance criteria.
- *DODAGID*, specifying one DODAG within one RPL instance.
- *DODAGVersionNumber*, which is incremented each time the DODAG is rebuilt.
- *Rank*, defining individual node positions with respect to the DODAG root. Its exact calculation is left to the objective function, but, to allow loop-detection, rank must monotonically decrease as the DODAG is followed towards the DODAG destination.

RPL provides a mechanism to disseminate information over the dynamically-formed network topology to enable minimal configuration in the nodes and to allow them to operate mostly autonomously. A key role in RPL is played by the DAG Information Option (DIO) messages, containing information about the rank, the objective function, IDs, and so on. They are broadcasted periodically by each node to create the DODAG.

To avoid redundancies and to control the signaling overhead, the *trickle* algorithm [17] triggers, for each node, a new DIO message only when the overall amount of control packets already sent in the neighborhood of that node is small enough. In the trickle algorithm, the time is split in an endless sequence of intervals with size I. A node can transmit a new DIO message at a random instant t in the second half of each interval if, since the beginning of that interval, the number of signaling messages (which have been heard) is smaller than a given threshold δ_{RC}, i.e., the *redundancy* constant. The size I is not fixed, but it is varied over the time in the range $[I_m, 2^M \cdot I_m]$. In particular, starting from the minimum size I_m, I is doubled, at the end of each interval, up to a maximum number of times M. When an *inconsistent* state is detected (e.g., there is the detection of a loop or the join to a new DODAG version), the trickle timer is reset; that is, I is set to the value I_m.

The root of the DODAG starts sending DIO messages with rank equal to 1. Upon DIO reception, nodes update their rank and the cost to the sink. Each node can select its parent (among those nodes having a lower rank) based on several possible rules, such as objective function, path cost, rank, and so on. A DODAG root can issue a global repair operation by creating a newer version of the DODAG. Nodes in the new DODAG can choose a new rank regardless their positions within the old DODAG Version. RPL also supports mechanisms, based on DIO messages, which may be used for local repair within the same DODAG version, e.g., upon loop detection.

When a node joins the WSN, it waits for a DIO message in order to discover possible parents. Optionally, a new node can multicast a DODAG Informational Solicitation (DIS) to ask for a DIO.

Finally, it is worth to note that nodes information can also be propagated upwards along the DODAG using the Destination Advertisement Object (DAO). These messages are used for handling downward and peer-to-peer traffic too (i.e., from sinks to the sensors and from sensor to sensor). These messages are triggered by the reception of a DIO message, or in global and local repair operations. After receiving a DAO message, each node forwards it to its parent on the expiration of a DelayDAO timer, which is implementation-dependent, according to [8].

III. Simulation Environments

To analyze the general behavior of RPL under different conditions, we have considered a wide range of simulation settings. In particular, we have evaluated (using the Contiki COOJA simulator [14]) scenarios with a single sink node, assuming a squared sensing area with a side $L = 200$ m. We have also considered a transmitting range $R_{tx} = 50$ m for all nodes, including the sink. Sensor nodes have been randomly scattered in the sensing area, subject to the constraint of obtaining a connected physical communication graph.

The number of nodes, N, in the sensing area has been varied within the range $[20, 100]$. For each value of N, 10 different random topologies have been simulated, thus obtaining 50 different DODAGs.

Figures 1 and 2 show example topologies obtained for a WSN with 20 and 100 nodes, respectively.

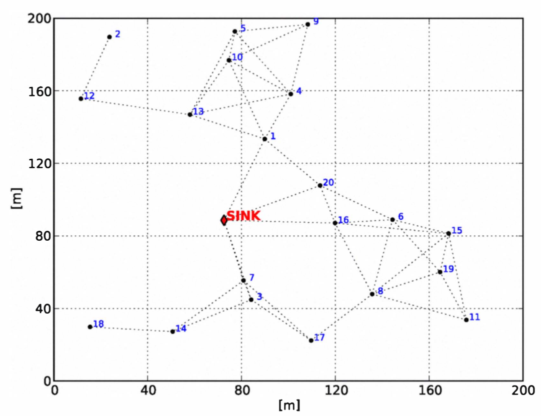

Fig. 1. Topology of a WSN with 20 nodes.

To test the strength of RPL under different loss conditions for each of the already described physical topologies, we have also considered four values (0, 0.01, 0.02, and 0.03) of Packet Error Rate (PER), according to the results shown in [18].

In simulations, the classic IEEE 802.15.4 MAC [19] is enhanced using the Low Power Listening (LPL) protocol [20], which allows the radio to stay off as much as possible in order to extend node battery lifetime. In particular, with LPL, each node performs short and periodic checks during which the channel is sensed to detect incoming packets. In this way, the power consumption burden is placed on the transmitter node,

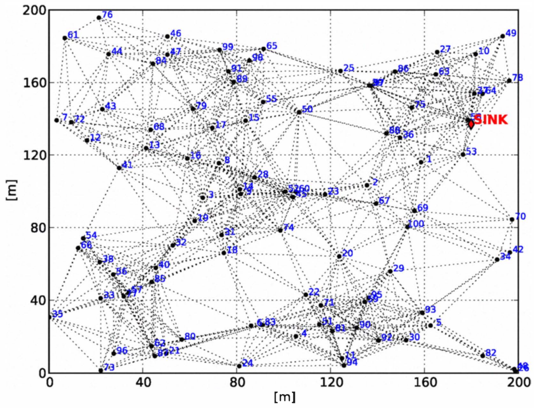

Fig. 2. Topology of a WSN with 100 nodes.

which continuously transmit the same packet (each copy of the same packet is referred to as *strobe*) to allow a correct check on the receiver side. This also mitigates the effects of random losses due to noise on the radio channel. The number of strobes is a LPL parameter. Unicast transmissions are acknowledged by the receiver in order to stop the transmitter sending strobes. To implement this feature, packet transmissions are interleaved with periods of silence to allow the reception of ACKs.

The 6LowPAN [21] has been used as IPv6 header compression at the network layer. RPL is obviously used as routing protocol. Trickle timer parameters have been set as, $I_m = 4.1$ s, $M = 8$, $\delta_{RC} = 10$. At the transport layer, UDP has been used.

To emulate low-rate scenarios, for which RPL has been explicitly conceived, each sensor generates a traffic of 70 bytes long messages per minute.

Node ranks have been defined using the Expected Transmission Count as suggested in [16],[22].

IV. Performance Evaluation

Herein, simulation results are reported in order to shed some light on the RPL behavior. With reference to the scenarios described in Sec. III, we will first analyze the signaling overhead and the network set-up transient. Then, we move our attention on end-to-end packet delays. The former analysis is useful to understand the energy efficiency of RPL (which is strictly related to the protocol overhead) and how it can be employed also in critical scenarios where a very limited set-up time is required. The latter, instead, describes the distribution of packet delays as a function of network size, channel reliability, and node rank.

A. RPL overhead and WSN throughput

Fig. 3 shows the overhead due to RPL, computed as the ratio of the total traffic due to RPL signaling, in a WSN with 20 nodes. From this plot, we can infer three important considerations: (i) the transient due to the routing set-up lasts about 10 minutes (i.e., the time required to let the overhead drop from 100% to about 25%); (ii) during the initialization of the WSN, almost all traffic circulating in the network is due to RPL signaling; (iii) at steady state, the overhead oscillates around 25% of the overall traffic.

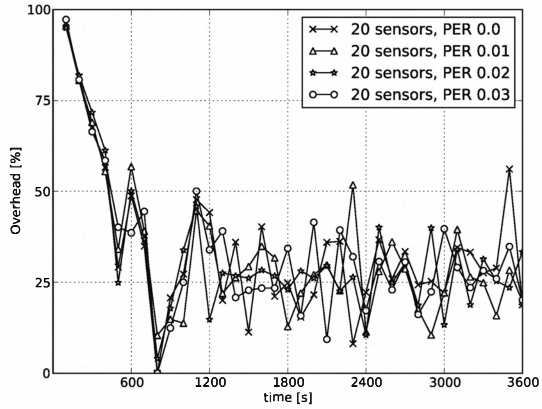

Fig. 3. RPL overhead in a WSN with node, for several PERs.

To demonstrate the effect of the RPL transient, Figs. 4 and 5 show the network throughput, computed as the amount of bytes received by the sink every 10 s, for a WSN with 20 nodes: the sink starts receiving data very soon after its deployment. Thus, RPL allows a very fast network set-up in the monitoring field. Analogous results for a WSN with 100 nodes are reported in Figs. 6 - 8. The main differences with respect to the previous case is a higher overhead and a slightly larger throughput transient duration due to the increased number of nodes. In fact, as we can observe in Fig. 6, at steady state the signaling messages contribute up to 75% of the total traffic, which is very larger with respect to the previous case.

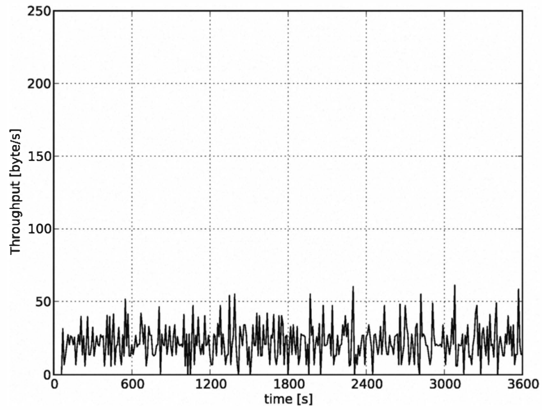

Fig. 4. Throughput for a WSN with 20 nodes (PER=0).

From these results we can conclude RPL is a valid routing protocol because, thanks to a very fast network set-up, can afford also critical scenarios such as rescue or military operations. On the other hand, the total overhead incurred for

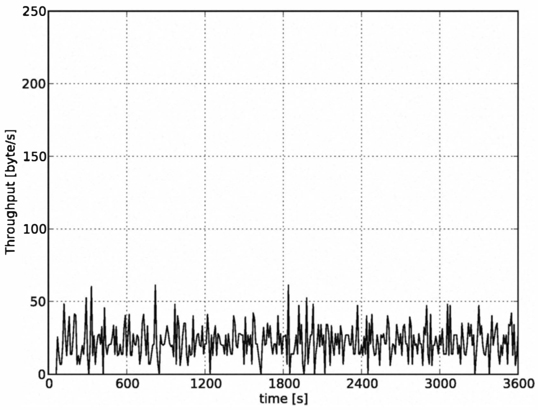

Fig. 5. Throughput for a WSN with 20 nodes (PER=0.03).

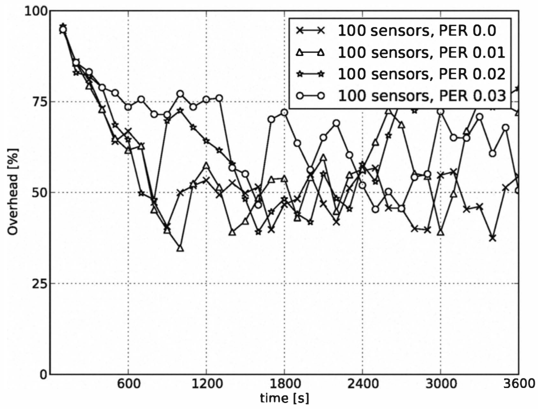

Fig. 6. RPL overhead in a WSN with 100 nodes, for several PERs.

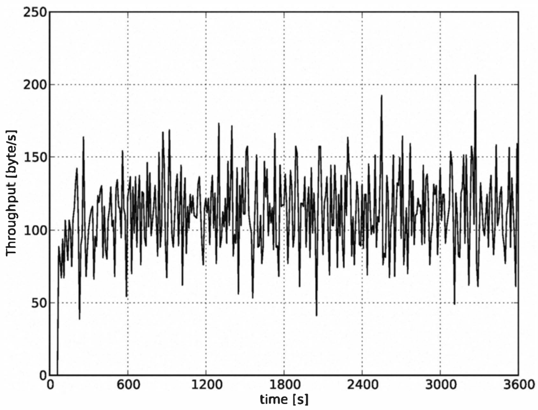

Fig. 7. Throughput for a WSN with 100 nodes (PER=0).

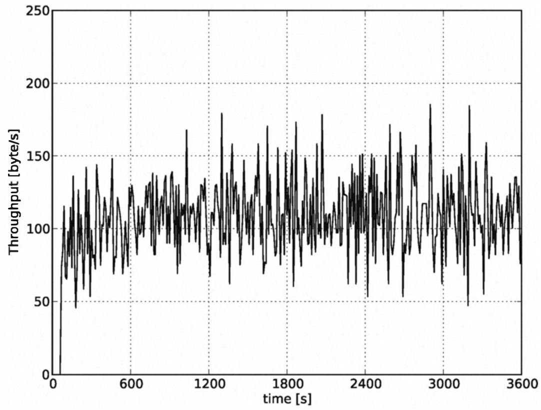

Fig. 8. Throughput for a WSN with 100 nodes (PER=0.03).

RPL signaling is very high if compared to the data traffic: this point deserves further research and protocol optimization. In fact, for a low rate sensing application running in a WSN with 100 nodes, such as the case considered herein (see Fig. 6), a protocol overhead oscillating from 30% to 75% means that a very high quota of energy resorces will be wasted for routing signaling.

To understand the reason of such a high overhead, we analyzed the impact of each kind of RPL message, i.e., DIO, DAO, and DIS. Figs. 9 and 10 report the results of this investigation for a WSN with 20 nodes (analogous results obtained for a network with 100 nodes are shown in Figs. 11 and 12). It is clear that in both cases DAO messages, which are optional, are responsible for the dominant component of the RPL signaling overhead. We briefly recall here that these messages are used to handle downward traffic from the sink to the nodes. This traffic could be used, for example, to query a specific region of the sensing area in order to acquire more information when an alarm is fired. As a consequence, to implement advanced WSN applications (with both upward and downward traffic) without spending a so high overhead signaling, timers require a fine calibration. Another important consideration is that overheads due to DIO and DAO messages are very different to each other; in fact, each DAO message has to be forwarded up to the sink whereas DIO messages are broadcasted only at one hop distance. Finally, the overhead due to DIS messages is negligible because these messages are generated only at the beginning of the simulation to let each node finding a neighbor.

B. Packet delays

Regarding network delays, Fig. 13 reports the CDFs of end-to-end packet delays in a WSN with 20 nodes. Delays are not very sensitive to the PER, which is mitigated by the LPL strobes (see also Sec. II). On the other hand, Fig. 14 shows that, as expected, packet delays are mainly related to the node distance from the sink (i.e., the rank). In any case delays are smaller than 2 s.

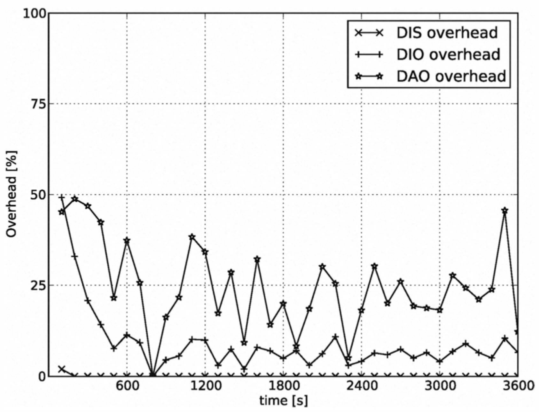

Fig. 9. RPL overhead in a WSN with 20 nodes for different kinds of signaling messages (PER=0).

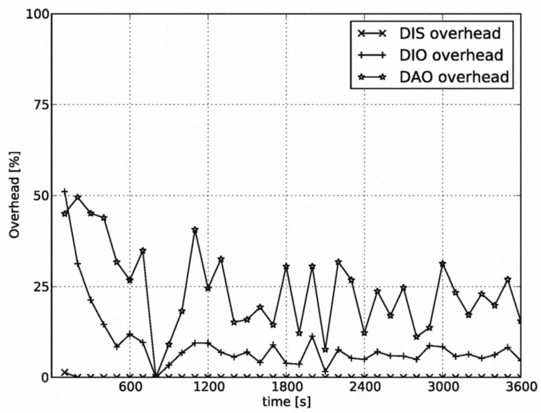

Fig. 10. RPL overhead in a WSN with 20 nodes for different kinds of signaling messages (PER=0.03).

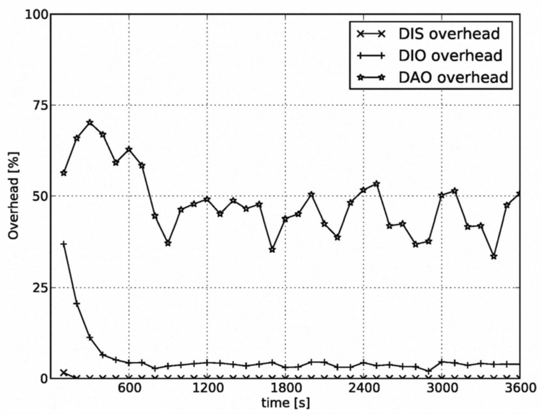

Fig. 11. RPL overhead in a WSN with 100 nodes for different kinds of signaling messages (PER=0).

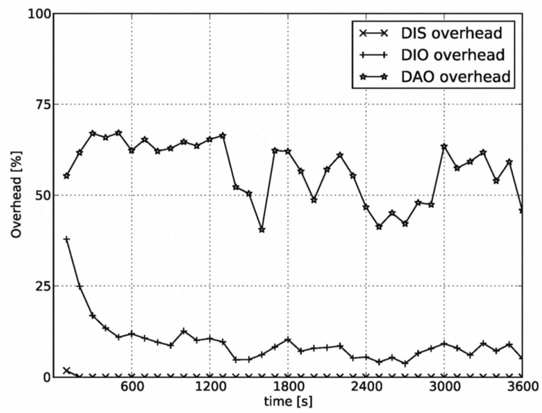

Fig. 12. RPL overhead in WSN with 100 nodes for different kinds of signaling messages (PER=0.03).

Analogous results obtained for a WSN with 100 nodes (see Figs. 13-16) lead to similar conclusions. Obviously, the larger number of nodes worsens packet delays, which can reach values up to 8 s. This effect is important because, depending on the application context, the network size can play an important role in the WSN responsiveness.

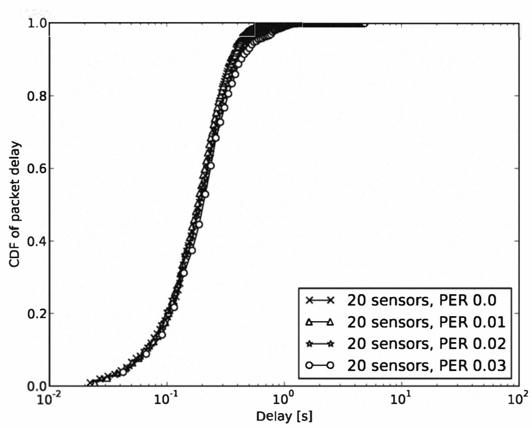

Fig. 13. CDF of packet delay for a WSN with 20 nodes.

V. Conclusions

In this paper, we presented a performance evaluation of the RPL routing protocol, using the Contiki COOJA simulator. Our results clearly indicate that: (i) RPL is a very powerful technique, granting a very fast network set-up and bounded communication delays; (ii) its effectiveness can be further improved in terms of overhead, which can be very high (up to 75% in steady state in a WSN with 100 nodes) due to DAO messages, used to handle sink-to-node downward traffic. Future investigations will also compare RPL with respect to routing protocols already available for WSNs.

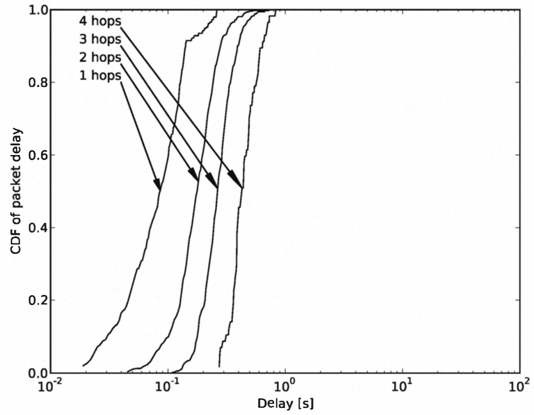

Fig. 14. CDFs of packet delay vs. rank for a WSN with 20 nodes (PER=0).

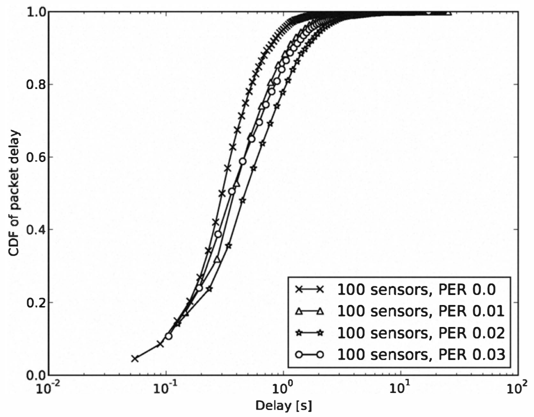

Fig. 15. CDFs of packet delay for a WSN with 100 nodes.

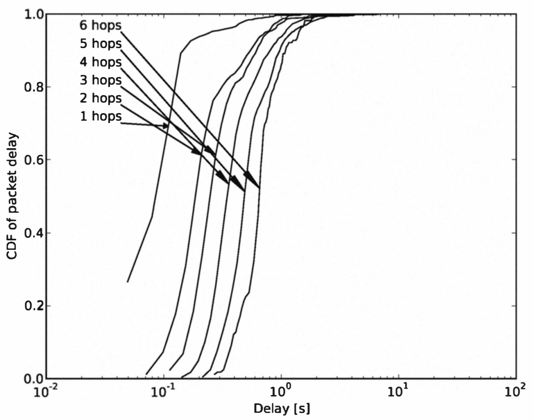

Fig. 16. CDFs of packet delay vs. rank for a WSN with 100 nodes (PER=0).

VI. Acknowledgments

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