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Reliable High Data Rate Wireless Sensor Network for Heavy-Lift Launch Vehicles

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Abstract

A typical new generation Heavy-Lift Launch Vehicle (HLV) has more than 600 sensors on board. More than 80% of these sensors are used for non-critical operational and technological data. This data is sent to the ground launching controllers allowing them to supervise, in real time or a posteriori, information concerning the state of the HLV and the progress of the launching operation. Sensors are traditionally connected to a concentrator entity using cables. The concentrator is a special node in charge of collecting data that is generated by sensors and transmit it to the ground controllers unit. The use of wireless technology to interconnect sensor nodes with the concentrator would allow an ease of deployment and a weight gain which will help achieve assembly time reduction and a gain in terms of generated power. Nevertheless, of-the-shelf wireless technologies cannot guarantee a wired equivalent reliability in terms of packet delivery ratio or end-to-end delay. Indeed, when transmitting over wireless communication links it is challenging to find a solution that avoids data loss especially in high data rate scenarios. This is essentially due to the nature of the wireless medium that is very sensitive to the surrounding environment and to the possible simultaneous multiple accesses to the medium by the different sensor nodes. In this paper, we propose a wireless solution based on the physical layer of IEEE 802.15.4 standard in the 2.4 GHz frequency band that enhances packet delivery ratio under an acceptable end-to-end delay threshold during all phases of the launching operation. The proposal is a multi-channel and multi-hop protocol that allows sensors that are deployed in the intersections of the HLV to communicate with a multi-radio interface concentrator node. Simulation results show promising performance in terms of packet delivery rate and end-to-end delay.

1. Introduction

Wireless technology is now widely used in our everyday life. It's ease of deployment makes it an interesting candidate for temporary installations. Applications using wireless communications vary from home automation to more critical industrial environments. In the Internet of Things era, billions of objects are expected to be connected to the Internet. They are able to exchange information with their surroundings in an autonomous way. Wireless protocols and standardization bodies, such as IEEE 802.11[1] and IEEE 802.15.4,[7] make sure this is possible when all communicating devices respect the technical specifications issued by these organizations.

One of the biggest challenges in wireless communications is to ensure reliability and robustness in confined areas for high data rate applications. Indeed, obstacles and interference affect network behaviour and degrade the overall performance. In this paper, we propose using wireless communications for interconnecting sensors deployed on board of a Heavy-Lift Launch Vehicles (HLV). Such wireless sensor networks are deployed for monitoring the sate of the HLV and sensors are requested to report data periodically to a control unit. This allows real time monitoring and offline analysis. A typical HLV has more than 600 sensors on board. More than 80% of these sensors are used for non-critical operations. Using wireless communications will significantly reduce the deployment phase and will also help to reduce the overall weight of the HLV. This type of applications are very time sensitive. Indeed, all data are requested to reach a collection point, called sink node, within 500 milliseconds. Hence, wireless protocols should be reliable enough to ensure minimal data loss and to respect the delay requirement.

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Sensor nodes are deployed in different sections of the HLV and some of them are not in range of the collection point. These nodes should be able to reach the sink through other sensor nodes. We propose a wireless protocol using the physical of IEEE 802.15.4. This physical layer has been tested inside a HLV and it proved to cope well within such a confined environment. The proposed protocol is able to reliably collect data packets and to respect the delay requirements of the application. Our proposal is based on HMC MAC (Hybrid Multi-Channel Medium Access Control) protocol.[3] Indeed, it is an adapted version that is designed to better fit the network characteristics deployed inside a HLV. The main features of HMC is the use of multiple radio interfaces on the sink node and multiple channels for data exchange among other nodes of the network.

The remainder of the paper is organized as follows. Section 2 presents the main multi-channel wireless communication protocols used for wireless sensor networks. Section 3 presents the main features of our proposal. In section 4, we discuss simulation results performance evaluation. We conclude the paper in 5.

2. Related work

Using multiple channels reduces interference generated by the transmissions of nodes that are part of the network. Hence, it helps to reduce collisions and data loss which results in improving throughput and achieving higher traffic loads compared to mono-channel protocols. MAC protocols are responsible for executing channel allocation algorithms and channel switching. Multi-channel MAC protocols for WSNs can be divided into three big families according to the method used for allocating channels: static channel allocation, semi-dynamic channel allocation, and dynamic channel allocation.

Static channel allocation protocols such as,[5][6] and[11] are known to be simple and generate less overhead in the network. On the other hand, the drawback of these allocation methods is that they are not suitable for dynamic network conditions such as frequent link failures or variation in the network topology. In addition, neighbouring nodes might not be able to establish direct link if they work on different channels.

In semi-dynamic channel allocation protocols such as,[3],[10] and[8] each node can communicate with its neighbours by switching to the right channel for each neighbour. However, semi-dynamic channel allocation require efficient coordination in order for sender and receiver nodes to be on the same channel at the same time. Also, switching channels might cause deafness problem and cause nodes to miss data packets destined to them when trying to communicate for a long duration with neighbors on different channels.

Dynamic channel allocation protocols such as,[9],[4] and[2] nodes switch channels in a systematic way at every transmission according to a frequency hopping scheme. This technique reduces interference and avoids using bad quality channels. On the other hand, proposed protocols have to frequently share control information globally or in a large neighborhood to negotiate channel allocation and coordination. Therefore, they cause considerable communication overhead to WSNs.

3. Hybrid Multi-Channel solution for HLV

Our proposed solution is based on HMC-MAC[3] protocol. It is a multi-channel MAC protocol that uses a semi-dynamic channel allocation and a multi-interface sink node. HMC-MAC operates on top of IEEE 802.15.4 physical layer in the 2.4 GHz frequency band. We adapted HMC-MAC in order to better suit the needs of HLV monitoring applications.

3.1 Network description

A typical wireless sensor network deployed in a HLV is constituted of 32 sensor nodes. There are 3 operation modes for nodes in the network: Low Rate mode (LR), High Rate mode (HR), and Very High Rate mode (VHR). Most of the nodes operate in low rate mode. LR nodes constitute 80% of the network and generate 5 samples per second. HR nodes generate 400 samples per second and constitute 15% of the network. VHR nodes generate 4000 samples per second and constitute 5% of the network. Each sample is an 8-bit data.

3.2 Network initialization

The sink node is the first node to be active in the network. All other nodes will remain in a listening mode waiting for a control message, that we call beacon, in order to detect the presence of the network. Beacon frames are sent on a specific control channel known to all the nodes. The sink is the first node to transmit a beacon. Nodes that are 1 hop away from the sink node will receive the beacon and know that they can reach the sink node using a direct link. Ideally, in order to optimize performance, the sink node should be placed in such a way to be 1 hop away from all HR and VHR

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Nodes type	Samples per second	Sent packets	Number of bytes per packet
VHR	4000	1 per 25 ms	100 bytes per packet
HR	400	1 per 25 ms	10 bytes per packet
LR	5	1 per 200 ms	1 bytes per packet

Table 1: Data packet rates and data samples for each node type.

nodes. LR nodes that are 1 hop away from the sink will transmit beacon frames. This way nodes that are 2 hops away from the sink will be able to detect the network and reach the sink by sending their data to intermediate LR nodes.

3.3 Channel allocation

HMC-MAC is based on a network discovery phase that allows nodes to dynamically allocate channels in a multi-hop network. Nodes that are 4 hops away can use the same channel without creating interference (this is case when MAC layer acknowledgements are used). In HLVs, the coverage zone is relatively small and wireless sensor nodes will be at most 2 hops away from the sink node. Indeed, this was confirmed with field measurements that we were able to establish inside a HLV. HMC-MAC is designed for larger networks. Thus, we simplified the channel allocation process of HMC-MAC as follows.

The sink node is equipped with 3 radio interfaces that will be working on 3 orthogonal channels. This allows the sink to increase its reception capacity and simultaneously receive data on 3 interfaces. With a physical data rate of 250 Kbps, 3 interfaces are enough to collect all data generated in the network. Channels that are used by the sink node will also be used by other nodes of the network. Thus, the whole sensor network will use 3 channels. This allows to deploy many sensor networks in the same physical space using different channels for each network. Note that the physical layer of IEEE 802.15.4 allows the use of 16 orthogonal channels in the 2.4 GHz frequency band.

3.4 Data exchange

When a node needs to send a data packet, it switches to the channel of the destination node and sends the packet using CSMA/CA of IEEE 802.15.4. For nodes that are 1 hop away from the sink, they will switch to the channel of one of the radio interfaces. The sink will announce in the beacon how many HR and VHR nodes it has on each interface in order for nodes to avoid sending data to overloaded radio interfaces. Nodes that are 2 hops away will choose one of their intermediate nodes and switch to its channel for data transmission. In case the link is broken with an intermediate node, a node can switch to another intermediate node after a certain number of unsuccessful transmissions.

For a deterministic channel sharing among different networks, channels can be affected to sink nodes, HR and VHR nodes in a predetermined manner in order to avoid congestions on certain channels.

4. Evaluation results

4.1 Simulation parameters and application scenario

We evaluated our proposal on NS3 simulator. Data samples are aggregated into data packets according to the mode of the nodes. Note that each sample is a 1-byte data element. Data samples are concatenated into packets in such a way to avoid generating a packet per data sample which will overload the network and the packet queues of nodes (packet queues size is fixed to 8 slots). Also, in order to respect the delay constraint of 500 ms which is requested by the application, we decided not to keep data samples longer than 200 ms in nodes. The packet generation rate and the data sample rate for each mode of nodes are given in table 1.

Results presented in what follows are averaged over 200 iterations. At each iteration we generated a new network topology with the same number of nodes. The random behaviour of CSMA/CA varies as well for each iteration. In addition, we used a probabilistic propagation model (LogDistance model) which also has a random component that varies for each iteration.

An example of a topology is given in figure 1 for iteration number 20. Blue dots represent LR nodes, yellow dots represent HR nodes, and red dots represent VHR nodes. The green dot is the sink node.

Note the 2 circles centred on the sink. The first circle represents the zone in which nodes can establish direct links with the sink. Note that this is only a simplified example, in the simulation the propagation model makes the

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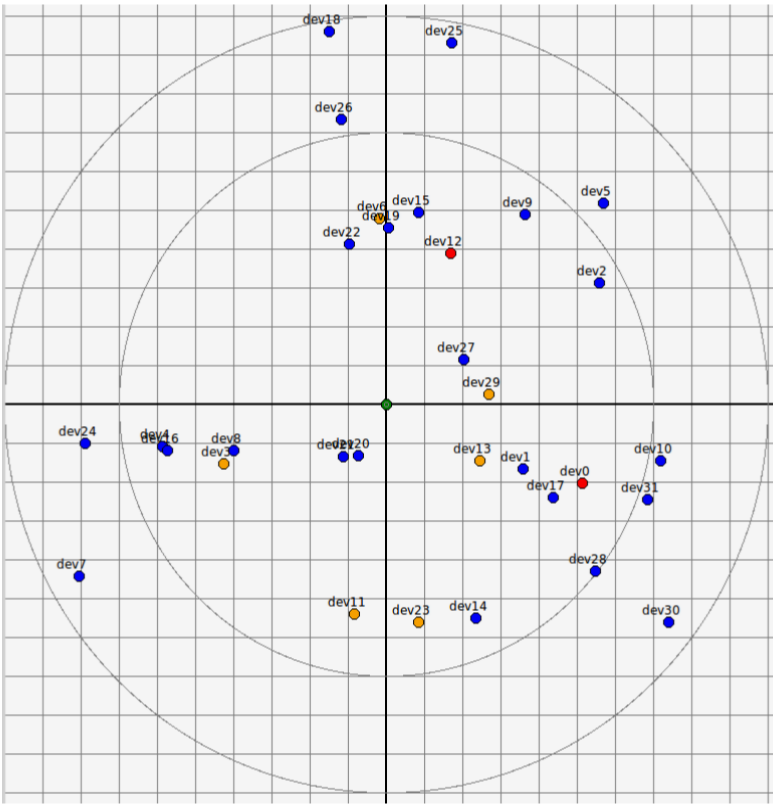

Figure 1: A topology example for iteration number 20.

coverage zone variable. Nodes that are positioned between the 2 circles are 2 hops away from the sink. Only LR nodes can be 2 hops away from the sink.

The application scenario that is simulated for the 200 iterations respects a sequence of phases. This scenario is the typical cycle in which a HLV goes during the launching operation. Each phase of the scenario has a specific operation mode during which part of the nodes are activated according to a specific mode. Each phase lasts for a certain duration according to figure 2. For each phase, we indicated the type of nodes that are activated.

Note that the cycle starts with a phase during which all nodes operate in LR mode. Also, all nodes are active in their respective modes only during phases FMT2, FMT4, Transitory phases, and FMT11. The grey bars separating the phases represent periods during which nodes should be reconfigured to function according to the up-coming phase. During these reconfiguration phases beacon frames are sent by the sink node to inform nodes of the upcoming change.

4.2 Delivery ratio results

The delivery ratio is the ratio of successfully received packets by the sink node over the total number of generated packets. Figure 3 shows the delivery ratio for each type of nodes and the total delivery rate for the whole network. Mean values are represented by the blue columns. Orange dots represent the standard deviation. Green dots represent the lowest delivery rates obtained over the 200 iterations.

As the delivery ratio results show, our solution is promising for it provides a delivery ratio of over 99% for the entire network over 200 simulations. The average delivery ratio being at 99,79%.

4.3 Delay results

In this section, we present results of delay. The delay is an important performance metric in this kind of applications. Indeed, the application needs all data samples to be received by the sink at most 500 ms after the generation of the data sample at each node of the network. In order to have a safe margin, we considered a threshold of 400 ms in the simulation results. This delay is thus calculated over the period between the creation of the data sample and the reception of this sample by the sink.

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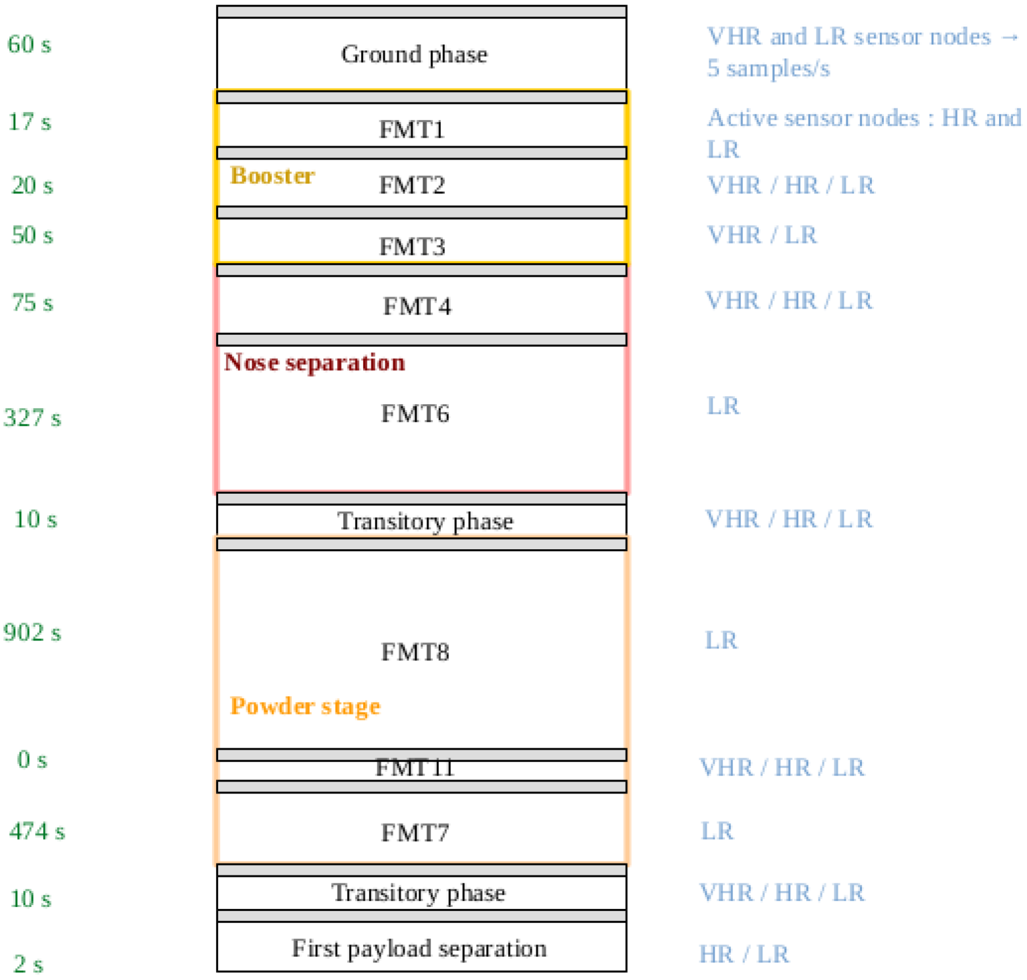

Figure 2: A description of a typical cycle of HLV activity monitoring during the launching operation.

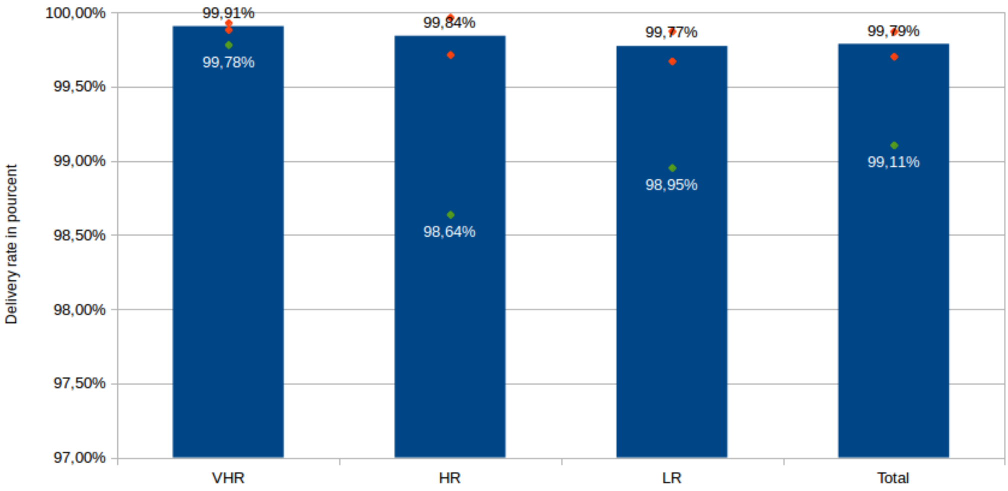

Figure 3: Average delivery rate for 200 iterations.

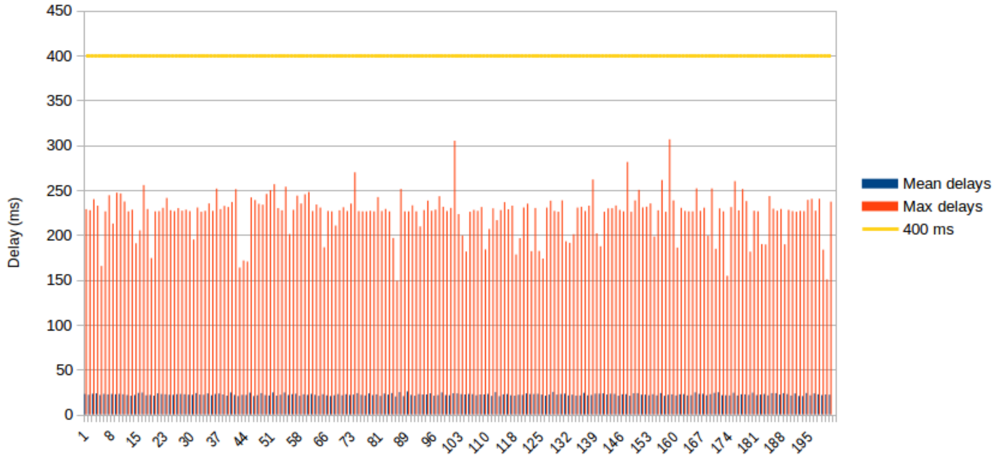

Figure 4: Average delay for data samples generated by VHR nodes for 200 iterations.

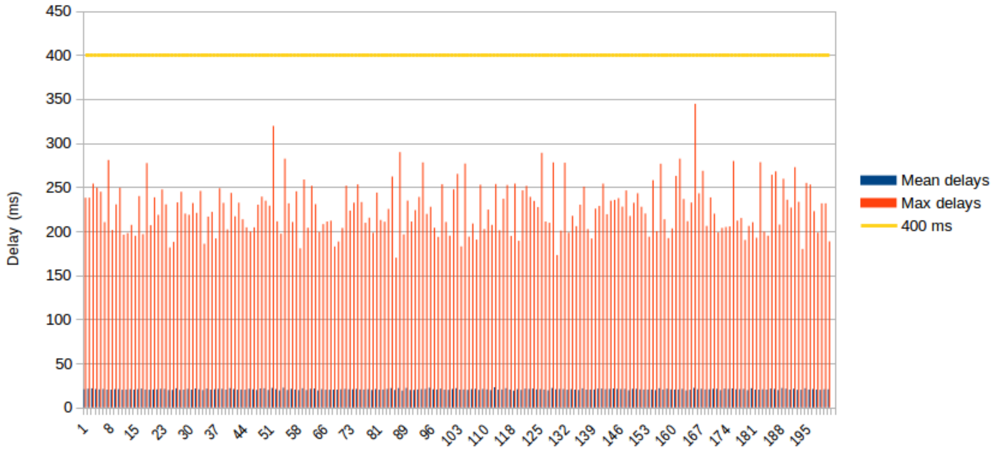

Figure 5: Average delay for data samples generated by HR nodes for 200 iterations.

The delay is calculate on a set of 200 simulations and for each type of nodes. Figures 4, 5, and 6 depict average delay values of data samples generated by all nodes of the same type for each iteration. These figures also show the maximum delay for each iteration. Note that the x axis of these figures indicates the iteration number.

Note that the average delay for all iterations is well below 400 ms. The maximum delay obtained for all 200 iterations for VHR and HR nodes are also all below 400 ms. On the other hand, for LR nodes, some of the sent packets are received with a delay higher than the 400 ms threshold. Indeed these data samples have to travel over 2 hops to reach the sink. In figure 7, we depict the number of data samples that exceeded this delay for each iteration.

More than 235 200 packets are sent by the 24 LR nodes. Only 100 to 200 packets have exceeded the delay threshold. This represents 0.085% of the total number of packets generated by LR nodes. In order to understand why these data samples exceed the delay threshold, we will analyse one iteration example and note the time at which the data sample that exceeded the delay was generated. Figure 8 depicts this information. We chose the iteration number 20.

This result shows that data samples that exceeded delay threshold for LR nodes where generated during the switching phases. Switching phases require control traffic (beacons) to be sent in order for nodes to adapt their traffic generation rate. When beacons are sent by 1 hop nodes, they are treated with a higher priority in the packet queues and thus create additional delays. Also, when nodes intermediate nodes are sending beacons they are unable to received packets from 2-hop LR nodes. This creates additional delay for data samples generated by 2-hop LR nodes.

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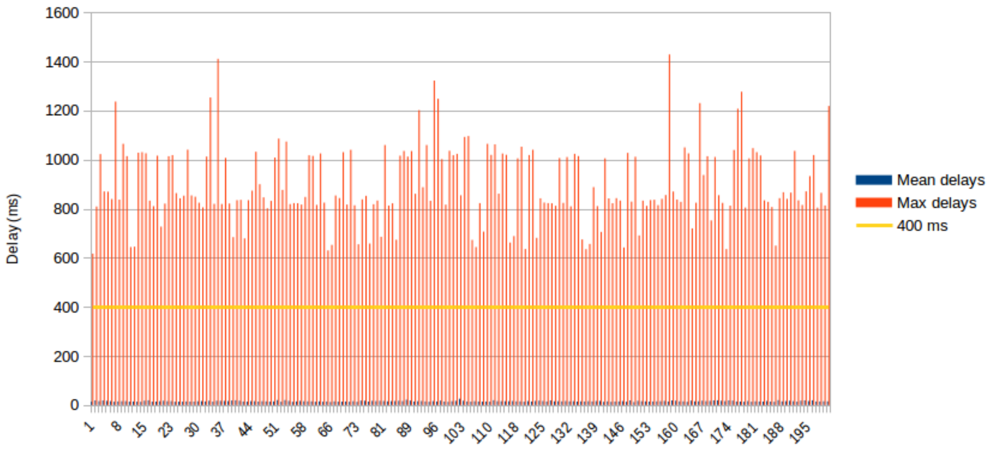

Figure 6: Average delay for data samples generated by LR nodes for 200 iterations.

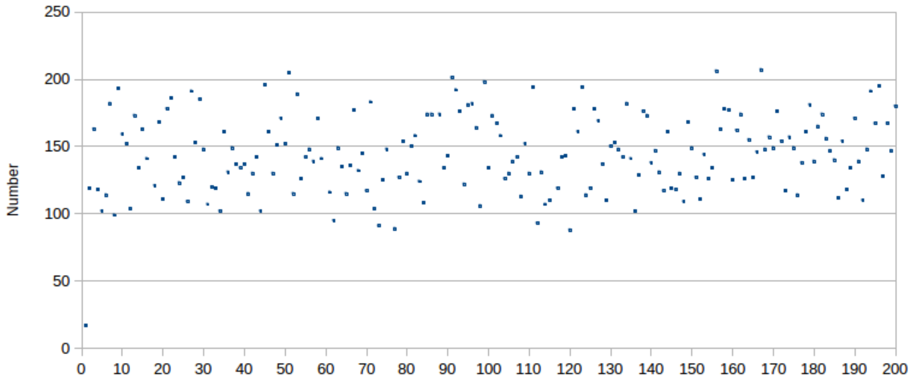

Figure 7: Number of data samples for LR nodes that exceeded the delay of 400 ms for each iteration.

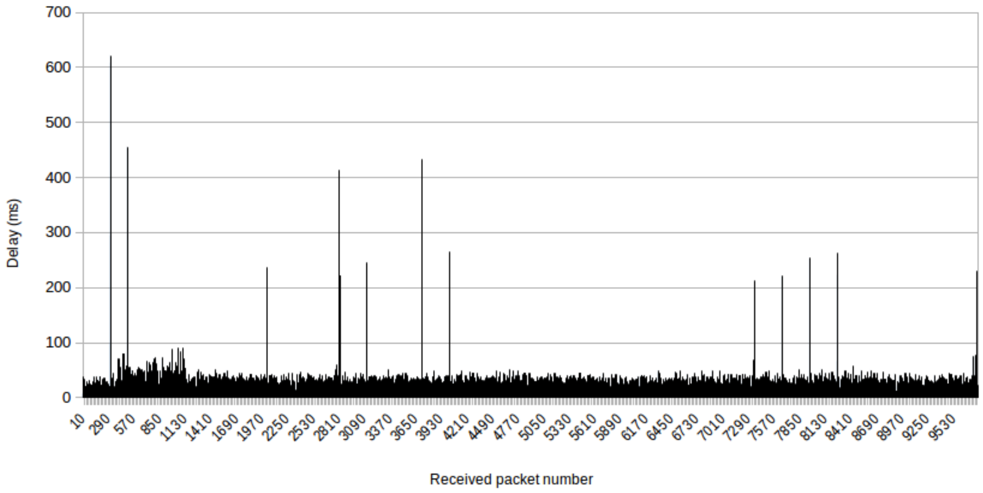

Figure 8: Time at which data samples exceeded the delay threshold.

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5. Conclusion

Using wireless sensor networks on board of HLV allows deployment facilities and weight reduction. Guaranteeing wireless transmission reliability for demanding applications in such a confined and obstructed environment is a challenging task. Monitoring the state of a HLV requires reliable transmission techniques. Wireless communications in confined areas such as launchers are prone to errors due to obstacles and interference. In this paper we proposed a wireless protocol that is able to guarantee the application requirements in terms of throughput, packet loss and delay. The network makes use of a multi-interface sink and multiple channels in order to optimize performance in dynamic data collection scenarios.

We have already tested the behaviour of the 2.4 GHz frequency band inside HLVs and results were positive. Nodes were able to establish good quality communication links with the presence of obstructing metallic objects. Our next step is going to be to implement our proposal on real nodes and to evaluate the performance of the solution inside HLVs which will help prove the robustness of the solution in real deployment scenarios.

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