Structural Health Monitoring Network System with Wireless Communications Inside Closed Aerospace Structures

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ABSTRACT

Structural Health Monitoring (SHM) requires integrated "all in one" electronic devices capable of performing analysis of structural integrity and on-board damage detection in aircraft's structures. PAMELA III (Phased Array Monitoring for Enhanced Life Assessment, version III) SHM embedded system is an example of this device type. This equipment is capable of generating excitation signals to be applied to an array of integrated piezoelectric Phased Array (PhA) transducers stuck to aircraft structure, acquiring the response signals, and carrying out the advanced signal processing to obtain SHM maps. PAMELA III is connected with a host computer in order to receive the configuration parameters and sending the obtained SHM maps, alarms and so on. This host can communicate with PAMELA III through an Ethernet interface. To avoid the use of wires where necessary, it is possible to add Wi-Fi capabilities to PAMELA III, connecting a Wi-Fi node working as a bridge, and to establish a wireless communication between PAMELA III and the host. However, in a real aircraft scenario, several PAMELA III devices must work together inside closed structures. In this situation, it is not possible for all PAMELA III devices to establish a wireless communication directly with the host, due to the signal attenuation caused by the different obstacles of the aircraft structure. To provide communication among all PAMELA III devices and the host, a wireless mesh network (WMN) system has been implemented inside a closed aluminum wingbox. In a WMN, as long as a node is connected to at least one other node, it will have full connectivity to the entire network because each mesh node forwards packets to other nodes in the network as required. Mesh protocols automatically determine the best route through the network and can dynamically reconfigure the network if a link drops out. The advantages and disadvantages on the use of a wireless mesh network system inside closed aerospace structures are discussed.

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INTRODUCTION

Structural Health Monitoring (SHM) systems imply the integration of non-destructive evaluation methods within a structure to enable autonomous state awareness for structural-integrity. SHM systems offer methods to reduce operational costs and improve the safety and reliability of aircrafts and other structures. The SHM approach can provide continuous monitoring, inspection, and detection of damage in structures with minimal human involvement.

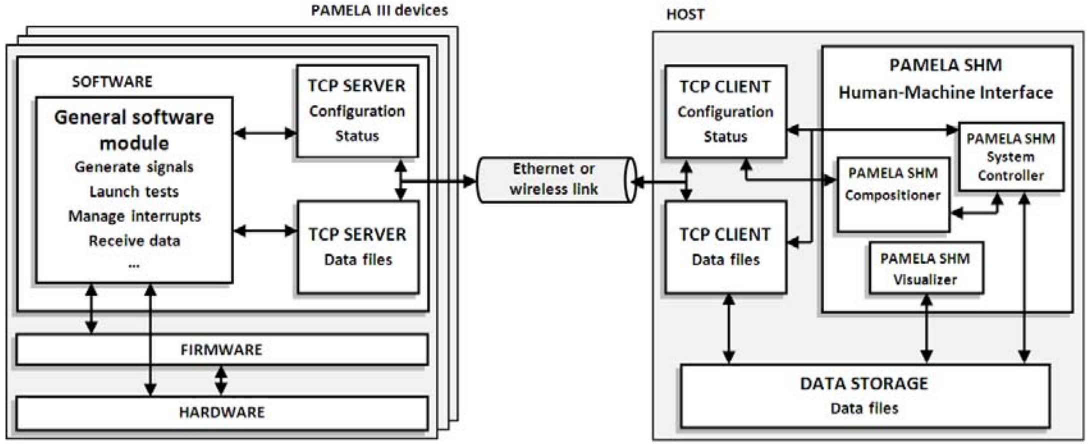
The Technical University of Madrid and the University of the Basque Country, under the direction of AERnnova Engineering Solutions Ibérica S.A, have developed an all-in-one electronic device capable of performing analysis of structural integrity and on-board damage detection in aircraft's structures, based on guided wave ultrasonic method. The device is called PAMELA III (Phased Array Monitoring for Enhanced Life Assessment, version III) SHM, and it integrates all the necessary hardware, firmware and software elements to generate excitation signals to be applied to an array of integrated piezoelectric Phased Array (PhA) transducers stuck to aircraft structure, acquiring the response signals, sending the data to a central host and/or carrying out the advanced signal processing to obtain SHM maps.

All hardware and firmware elements have been developed by the Electronics Design Group of the University of the Basque Country. The implementation details are described in [1][2][3][4]. The development of software elements was carried out by the Applied Acoustic Research Group of the Technical University of Madrid at CAEND. Amongst the software elements, the software communication module is one of the most important, because in a real aircraft scenario, several PAMELA III devices must work together inside closed structures, and must be communicated with the central host in order to be configured and to send data collected and/or processed. To avoid wiring between the system elements is one of the aims of the work, in order to reduce the weight of the entire system, to increase deployment flexibility and to decrease the maintenance costs. In this sense, a wireless mesh network (WMN) system has been implemented inside a closed aluminum wingbox to provide communication among all PAMELA III devices and the central host or a laptop.

The paper describes the most important software elements and characteristics of the whole system, with particular emphasis on system communication approach.

PAMELA SHM™ SOFTWARE ARCHITECTURE

PAMELA SHM™ system includes a host computer and one or several PAMELA III devices connected to it. PAMELA SHM™ software elements are divided into two categories: software modules running in PAMELA III devices and software modules running in the host, as shown in Fig. 1.



a) Running in PAMELA III device ***b) Running in the host***

Figure 1. PAMELA SHM™ software architecture.

Each PAMELA III device has its own IP address and, of course, several PAMELA III devices can be working simultaneously connected to the external host. In order to simplify the maintenance of the entire system, PAMELA III devices can be configured to boot over the network, loading their operating systems from an external server (not represented in Fig. 1). Thus, all system devices are updated with the latest version of the software when booting. With this method, no physical access to devices is required. For this purpose, TFTP boot method is used.

There are three main modules, written in C language, running in PAMELA III device. This use an embedded Linux OS running on the embedded PowerPC include in a XILINX FPGA. The software module implements two TCP servers, one for receiving data configuration from host and for sending status information, and another in charge of sending acquired data files to the host after the completion of each test. The main software module is in charge of the communication with the firmware and hardware to generate excitation signals, to manage interrupts, to perform the tests, and to obtain the result data files.

On the other hand, the software running in the host is written in LabVIEW language and can be executed over Windows or Linux OS. The host software are divided into four modules: two TCP clients that communicate with their respective servers in PAMELA III; the data storage module, responsible for the conversion of the data received from PAMELA III and the storage of the generated files; and the human-machine interface (HMI), composed of several applications, such as PAMELA SHM™ Compositioner, PAMELA SHM™ System Controller and PAMELA SHM™ Visualizer.

The system can perform several types of tests: passive, simple, round robin, transmitter beamforming, transmitter focusing, time reversal (simple and round robin), and plane front [1], with selectable wave velocities, sampling frequency and number of samples per test. The excitation signals are fully configurable in shape, frequency, amplitude and number of pulses. The type of excitation signals includes sine, sine sweep, impulse, uniform white noise and arbitrary, with several windowing as Hamming, Hanning and Flat.

Fig. 2 shows two screenshots of the PAMELA SHM™ System Controller module. The first one displays the parameters and evolution of a transmitter beamforming test, while the second one displays the configuration for a transmitter focusing test.

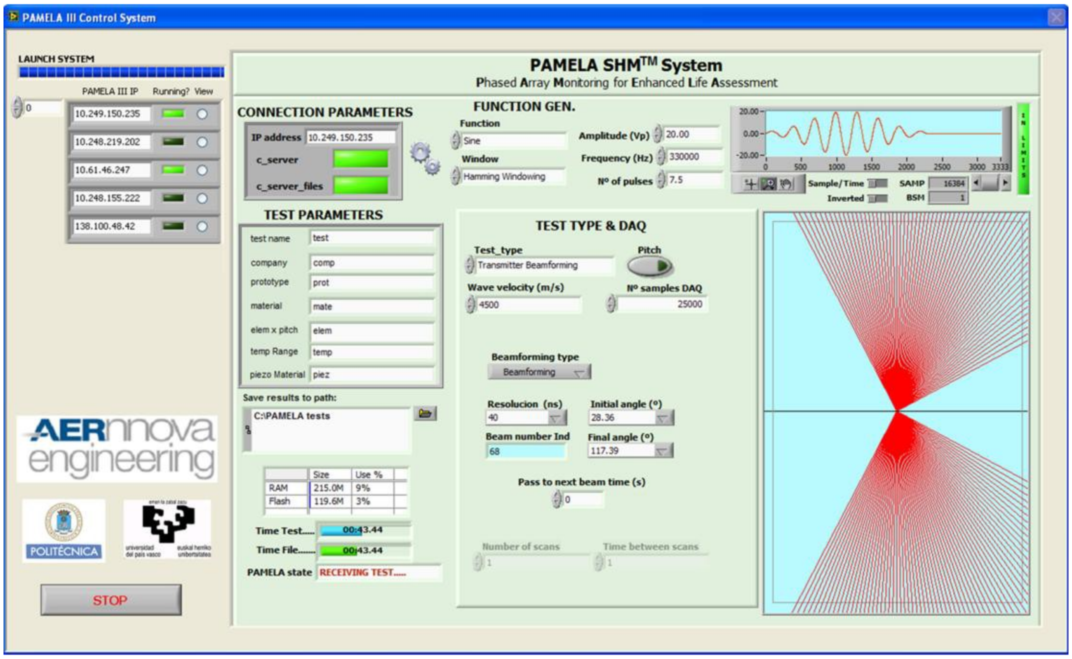


Figure 2a. PAMELA SHM™ System Controller HMI. Example of transmitter beamforming test.

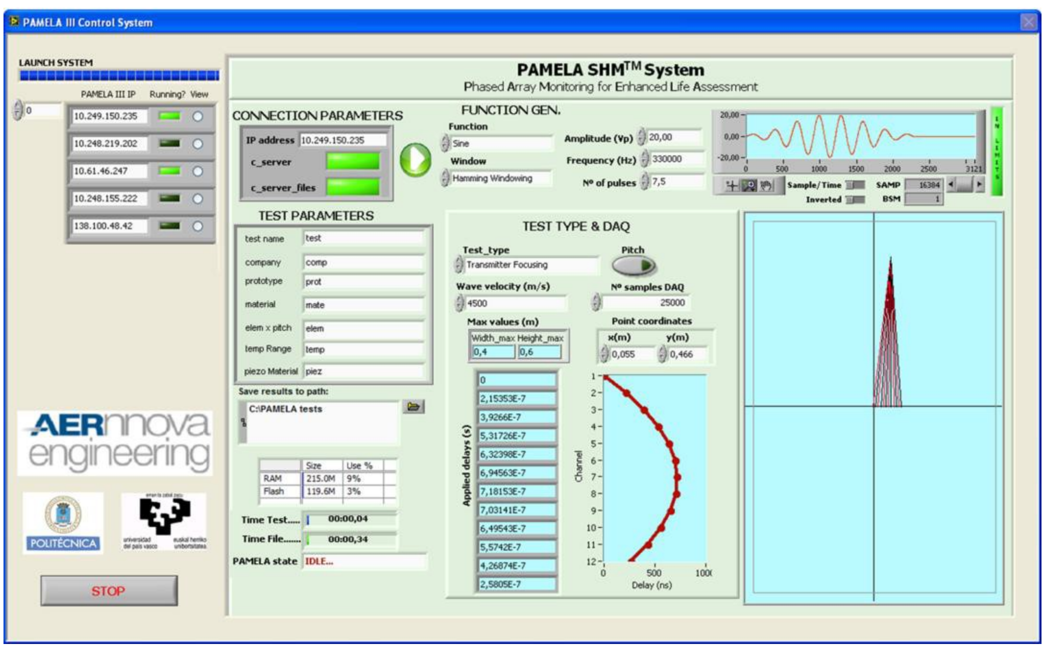


Figure 2b. PAMELA SHM™ System Controller HMI. Example of transmitter focusing test.

Fig. 3 shows the PAMELA SHM™ Visualizer with some of the time signals obtained from a transmitter beamforming test shown in Fig. 2. Each row represents the data obtained from a specific angle (D_i) when applying the corresponding delay. Each column represents a specific channel, linked to a specific transducer. The displayed data correspond with the data received from a PAMELA III device, without any processing algorithm applied to data. However, PAMELA SHM™ system are capable, if programmed, to run in autonomous mode, periodically making structural tests, applying processing algorithms to the acquired data, and sending to the host only the results of the structural integrity analysis (SHM maps, alarms and so on).

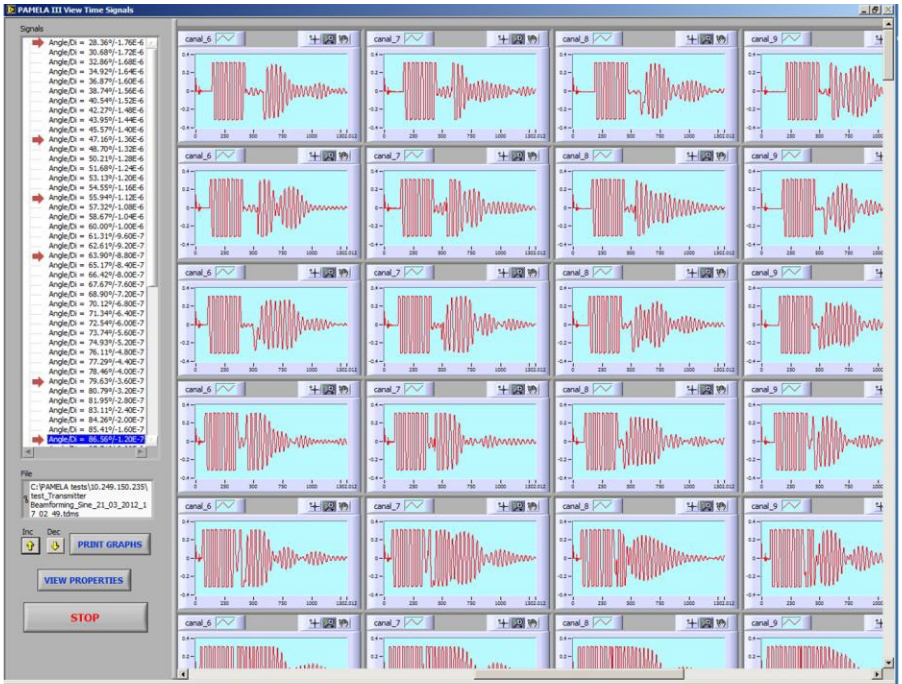


Figure 3. PAMELA SHM™ Visualizer HMI. Time signals obtained from a transmitter beamforming.

PAMELA SHM™ COMMUNICATIONS APPROACH

The previous paragraphs describe the software architecture of PAMELA SHM™ system, that includes a host computer and one or several PAMELA III devices connected to it. In a laboratory scenario it is possible to use Ethernet cables and switches to connect the host to all PAMELA III devices in the system. However, in a real aircraft scenario, several PAMELA III devices must work together inside closed structures. In this case, the use of wired systems should be avoided. A solution based on establishing wireless links between devices and the host is a better approach.

In closed structures it is not possible for all PAMELA III devices to establish a wireless communication directly with the host, due to the signal attenuation caused by the different elements of the aircraft structure. Therefore, it is necessary the deployment of a wireless mesh network (WMN) system that provides fully communication among all devices located inside the structure and the host. In a WMN, as long as a node is connected to at least one other node, it will have full connectivity to the entire network because each mesh node forwards packets to other nodes in the network as required. Mesh protocols automatically determine the best route through the network and can dynamically reconfigure the network if a link drops out. In this way, the host only needs to establish direct communication with one device inside the structure, as long as all devices can establish direct communication at least with one other.

Wireless alternatives

There are several alternatives to develop a wireless network. Bluetooth (over IEEE 802.15.1), ZigBee (over IEEE 802.15.4), and Wi-Fi (over IEEE 802.11) are standard protocols for short range wireless communications [5]. Table 1 shows a comparison between these alternatives.

	Bluetooth	**Zigbee**	**Wi-Fi**
IEEE standard	IEEE 802.15.1	IEEE 802.15.4	IEEE 802.11
Frequency band	2.4 GHz	868/915 MHz 2.4 GHz	2.4 GHz 5 GHz
Max signal rate	1 Mb/s	250 Kb/s	54 Mb/s
Nominal range	100 m	10 – 100 m	100m
Basic cell	Piconet	Star	BSS
Extension of the basic cell	Scatternet	Cluster tree Mesh	ESS, Mesh (802.11s)
Max number of cell nodes	8	>65000	2007
Power consumption estimation (mW)	100	90	650
Normalized power consumption estimation (mJ/Mb)	100	360	12

Table 1. Comparison of the Bluetooth, Zigbee and Wi-Fi protocols.

Based on the above information, Wi-Fi protocol appears as the best choice for the aims of the related project, as it offers the higher bandwidth, the lower normalized power consumption (extremely important for the application), and the possibility of developing a mesh network over IEEE 802.11s specification. A high bandwidth is essential in the first phase of the project because all data acquired by PAMELA III devices must be sent to the host for analysis purposes. In a final scenario, each PAMELA III device will perform its own structural integrity analysis and will send to the computer only the final results (SHM maps), so that the bandwidth requirements will be lower.

Test bed implementation

A test bed system has been developed to test the performance of the Wi-Fi mesh network. Several PicoStation2 nodes from Ubiquity Networks [6] have been used to provide Wi-Fi connectivity to PAMELA III devices. Table 2 shows PicoStaion2 main features.

Processor Specs	Atheros MIPS 4KC, 180MHz
Memory Information	32MB SDRAM, 8MB Flash
Networking Interface	1 X 10/100 BASE-TX (Cat. 5, RJ-45) Ethernet Interface
Antenna	RP-SMA omni antenna included
Power Supply	12V, 1A DC, Supply and injector included
Power Method	Passive Power over Ethernet (pairs 4,5+; 7,8 return)
Operating Temperature	-20C to +70C
Weight	0.10 kg

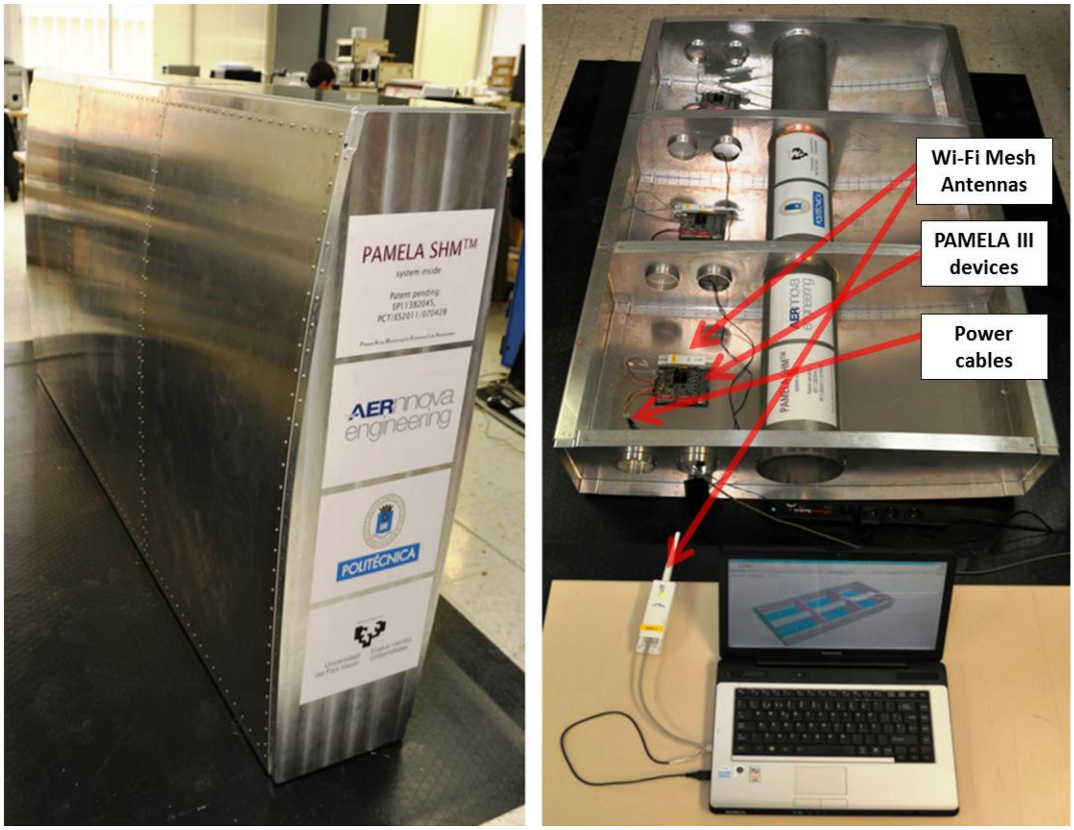
Table 2. PicoStation2 main features.

PicoStation2 offers Wi-Fi communication to any device connected to it. However, to make possible the node works in a mesh network, it is necessary to change the initial firmware of the PicoStation2 nodes. For this purpose, a Nightwing-wa firmware, based on OpenWrt [7], has been installed in the PicoStation2 nodes. Nightwing-wa uses BATMAN (Better Approach To Mobile Adhoc Networking) protocol for managing a wireless mesh network [8]. In this way, it is possible to develop a Wi-Fi mesh network among several PAMELA III devices and one host, simply connecting one modified PicoStation2 to each Ethernet connector of PAMELA III devices and the host. PAMELA III devices provide power supply to the nodes through the Ethernet cable using the POE capabilities of these ones.

When PAMELA III boots, the node, using DHCP, assign an IP address to it and, automatically, makes visible the new device to all other nodes of the mesh network.

Fig. 4 shows the details of the test bed used to analyze the operation of the mesh network. An aluminum wingbox consisting of three bays and removable covers has been used. Several PAMELA III devices (connected each one with one modified PicoStatio2 node) have been positioned inside the structure. Fig. 4 shows that there is an aperture between contiguous bays used to pass the power supply cables of PAMELA III devices. Another modified PicoStation2 node has been connected to a laptop. An USB connector of the laptop provides power supply to this node.

A set of communication tests, both with the structure open and close, have been performed to analyze the operation and performance of the mesh network. PAMELA SHM™ System Controller has been used to perform different test types in various PAMELA III devices alternative or simultaneously. Another application, PAMELA SHM™ Compositioner (shown in Fig. 5), allows the visualization of Wi-Fi communication paths in the mesh network. Compositioner software tool shows how the communication paths change when power off or power on one or several PAMELA III devices.



a) Closed wingbox ***b) Details of the wingbox interior***

Figure 4. Test bed implementation.

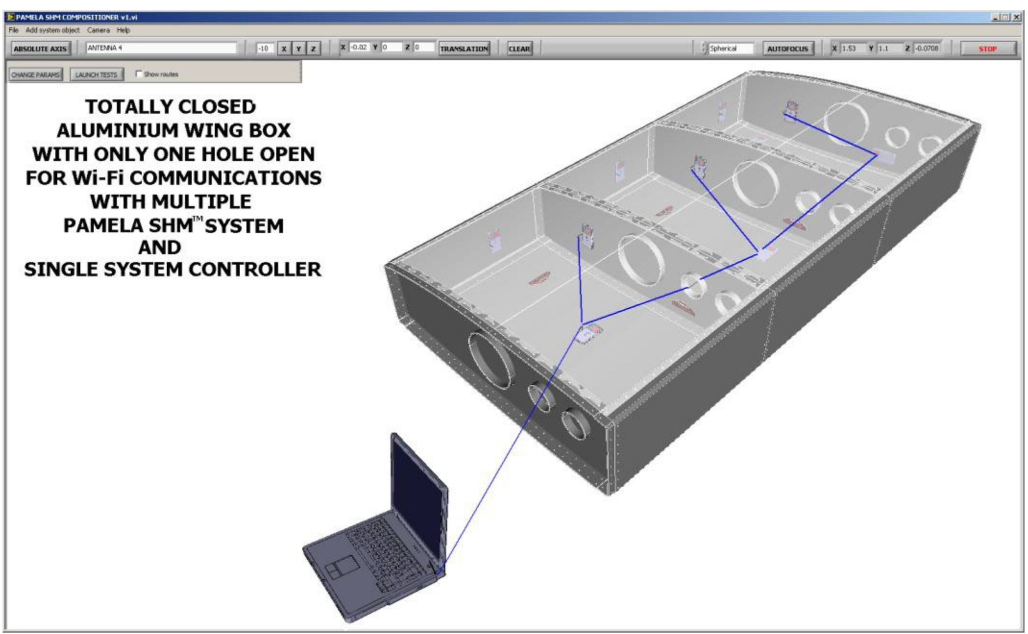


Figure 5. PAMELA SHM™ Compositioner HMI. Software tool for visualization of Wi-Fi communication paths in closed or open aerospace structure.

When the aluminum structure is open, the performed tests indicate that the communication path is established directly from laptop to each PAMELA III device. In this scenario, the performance of the network is optimal, and the maximum data rate measured in the laptop network adapter is closed to 13Mb/s. When the structure is closed, the Compositioner tool shows that it is not possible to establish a direct communication between the laptop and all the PAMELA III devices, so the mesh network needs to change the communication paths. In this new scenario, communication between two end nodes is carried out through a number of intermediate nodes, resulting in a multi-hop behavior, in a similar way that shown in Fig. 5. In this case, the performance of the network decreases in a factor that varies between 1/N and $1/2^{N-1}$, when N is the number of hops [9][10].

CONCLUSIONS

PAMELA SHM™ System is capable of performing analysis of structural integrity and on-board damage detection in aircraft's closed structures using a wireless mesh network (WMN) based on Wi-Fi technology. All capabilities of PAMELA III devices are available either by using an Ethernet communication or by using a WMN, without making any changes to the software modules of the device itself or the host. The update of the system components with the latest version of the software is automatic by using booting over network, so no physical access to devices is required.

The main drawback of the system is related with the decrease of the performance of the network when multiple hops are needed. Therefore, it will be necessary to research about other routing protocols [11][12] or multi-channel considerations [13].

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