Study the performance of the Zigbee Communication in an Aircraft Environment

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Abstract
This paper presents the future concept of flight control systems that is use zigbee technology in aircrafts, which can be used for aircraft functions controlling, monitoring and communication. This technology can be employed for any kind of air vehicle including, Aerial Vehicles, Jet air craft, commercial air craft etc. Nowadays, a fly-by-wire (FBW) flight control system of Air vehicles is employed for last few years in aircrafts through which the internal and external functions of aircraft are controlled and monitored by electrical signals which are transmitted and received by electrical wires. The idea of this paper is to implement the Zigbee wireless sensor network on any air vehicle to control and monitor the internal and external functions data due to its advantages over the electrical wires and this by establish a wireless connection between engine sensors which are mounted in the aircraft wings and the controllers inside the aircrafts cabin. This mechanism will bring remarkable improvements in the field of avionics and aerospace by reduce weight of aircraft, reduce fuel consumption and increase aircraft safety. Used methodology of the research constitutes the simulations of radio waves propagation, which were carried out based on earlier designed aircraft wing models. The simulations have been produced in Concept II simulation software package.
The analysis was undertaken in terms of, scattering parameters, the characterisation of radiation, interference effects of obstacles and other structures found in the wing as well as the influence of wing shape upon radio wave propagation within the wing. The simulation result shows that, the coupling between the antennas is very weak in 2.4 GHz bandwidth and the coupling between the ZigBee antennas is much lower than expected typical minimal SNR value. Also it reveals that, the influence of wing shape as of the antennas positions and multiple antennas appearance at 2.405 GHz frequency have highly impact upon the Zigbee wireless sensor network (WSN) performance.

**Keywords:**
Unmanned Aerial Vehicles, Interferences and Scattering Phenomenon in Cavities, Radio Wave Propagation, Wireless Networks, Wing Structures Modelling and ZigBee technology.

**1- Introduction**
The world of wireless telecommunications is witness rapidly evolving. The most common wireless technologies available nowadays such as GSM, Bluetooth and WiFi are all targeted towards sending large amount of data at relatively high speeds making the construction of such networks often complex and with relatively large financial overheads. Combined with the wireless sensor network (WSN), the ZigBee technology becomes one of preferred technologies in the wireless sensor network. It has the characteristics of consumption, low power, low cost, large network capacity, security, flexibility and powerful anti-interference ability. ZigBee technology is mainly a wireless sensor network implemented for various monitoring applications such as health, industrial, environmental and security systems. The technology has been designed to be self-healing and reliable to support a large number of nodes. It, also easy to deploy, standardised and it can be
used globally. Zigbee technology also relies upon IEEE 802.15.4, which has excellent performance in low signal to noise ratio (SNR) environments such as that found in an aircrafts due to environmental exposure and engine noise/vibration. In spite of that, it is unknown yet whether it is capable of delivering the same level of performance and reliability as wired looms.

Since the Modern passenger aircrafts contains around 150 miles of wiring and significant amount of harnesses which contribute considerably to the overall weight and consequently reduces fuel economy. Although wires and their insulators are designed to stand extreme environmental exposures, the inspecting and troubleshooting of wiring failures have a significant impact on maintenance costs. Using ZigBee technology, the wireless sensor network in aircrafts condition monitoring has less wirings and high automation. It can very fast layout and monitor data, transmit real-time dynamic information, reduce overall system weight, cost and increase the reliability of the system. This technology brings the aircrafts monitoring and fault diagnosis to a new level and promoted effectively the development of aviation technology. In particular, the objective here is to use a wireless network to facilitate communications between the engines sensors/switches located in the wings and the control units located within an aircraft’s cabin. For that, there is a need to understand and characterize the exceptional wireless channel used for this application, which basically is within the aircraft wing. Propagation in such a semi-hollow cavity will differ considerably than that in free-space or indoor channels due to the resonance effects depicted by the wings geometry. There are several design issues that need to be addressed in order to come up with a viable wireless engine sensor network in aircrafts. Based on the application of requirements, a wireless sensor network system for
aircrafts condition monitoring and its node design using WSN technology and new sensors together are proposed.

2- What Is ZigBee?
ZigBee is a standard that defines a set of communication protocols for low-data-rate short-range wireless networking [14]. ZigBee is targeted mainly for battery-powered applications where low data rate, low cost, and long battery life are main requirements. In many ZigBee applications, where wireless device is engaged in any type of activity, the total time is very limited, the device spends most of its time in a power-saving mode. As a result, ZigBee enabled devices are capable of being operational for several years before their batteries need to be replaced. The ZigBee standard is specifically developed to address the need for very low-cost implementation of low-data-rate wireless networks with ultra-low power consumption. The minimum requirements to meet ZigBee and IEEE 802.15.4 specifications are relatively relaxed compared to other standards such as IEEE 802.11, which reduces the complexity and cost of implementing ZigBee compliant transceivers. [4] One of the key characteristics of the ZigBee standard is its mesh networking capability. In a large distributed mesh network, a message is relayed from one device to another until it reaches its faraway destination.

The interface between a ZigBee network and other networks using a different standard provides by using a ZigBee gateway. For example, if ZigBee wireless networking is used to gather patient information locally inside a room, the information might need to be transmitted over the Internet to the monitoring station. In this case, the ZigBee gateway implements both the ZigBee protocol and the Internet protocol to be able to translate ZigBee packets to Internet protocol packet format, and vice versa. The name ZigBee was selected as a metaphor for the way devices on the network find and interact with one another [8].
3- The Relationship between ZigBee and IEEE 802.15.4 Standards

One of the common ways to establish a communication network (wired or wireless) is to use the concept of *networking layers*. Each layer is responsible for certain functions in the network. The layers normally pass data and commands only to the layers directly above and below them. ZigBee protocol layers are based on the Open System Interconnect (OSI) basic reference model [10]. Dividing a network protocol into layers has a number of advantages, for example, if the protocol changes over time, it is easier to replace or modify the layer that is affected by the change rather than replacing the entire protocol. Also, in developing an application, the lower layers of the protocol are independent of the application and can be obtained from a third party, so all that needs to be done is to make changes in the application layer of the protocol. As shown in Figure (1), the ZigBee standard defines only the networking, application, and security layers of the protocol and adopts IEEE 802.15.4 PHY and MAC layers as part of the ZigBee networking protocol. Therefore, any ZigBee-compliant device conforms to IEEE 802.15.4 as well [3].

![Figure (1): ZigBee Wireless Networking Protocol Layers](image)
4- Antenna Options
Any wireless device has an antenna, and antennas come in different shapes, sizes, gains, and impedances. Selecting the right antenna for an application can have a considerable impact on the overall performance. There are different types of antennas such as Dipole Antennas, Quarter-Wave (Monopole) Antennas, Tilted Whip or Open-Stub Antennas, Inverted F Antennas, Slot Antennas, Patch Antennas, Spiral Antennas, Helical (Coil) Antennas, Chip Antennas, and Small Loop Antennas.

5- Scattering Parameter
S21 parameter is one of four scattering parameters. The scattering parameters constitute the reflection and transmission coefficients between the incident and reflection waves. In electrical theorem they represent input/output relationship in the electric system. These parameters are measured by sending a single frequency signal into network and detecting what waves exit from each port.

6- Modeling the Wing and Wireless Network
The wing models were created by using Catia software (Wireframe and Surface Design Module). These models are model NACA64A410 wing with inner structure, Empty NACA64A410 wing model and Empty prismatic wing model, as shown in figure(2) and (3). All dimensions of the wing had been chosen and selecting the wing size was relied on a design of passenger aero plane, called “Ourania” and all these described in the publications. [13]. [7]. [2]. [12].
The empty prismatic representation of the wing (See Figure (3)) was used to check influence of the wing’s shape upon the radio wave propagation.

The models were meshed in G mesh software. All three modeled wings were imported into Catia application. The mesh refinement tool, which was twice used, decreases patches size and their number and further, to increase the accuracy for numerical calculation in the simulation software. It was needed to use the same parameters for all of the wing models to ensure the
same level of precision for simulations for different models geometry. Table 1 shows results of meshing for each model.

<table>
<thead>
<tr>
<th>Wing Model</th>
<th>Number of Nodes</th>
<th>Number of Patches</th>
</tr>
</thead>
<tbody>
<tr>
<td>NACA64A410 wing with inner structure</td>
<td>1540</td>
<td>2448</td>
</tr>
<tr>
<td>empty NACA64A410 wing</td>
<td>199</td>
<td>388</td>
</tr>
<tr>
<td>empty prismatic wing</td>
<td>194</td>
<td>384</td>
</tr>
</tbody>
</table>

The selection of the appropriate mesh size using mesh refinement function was dictated by the computational power of the PC station, which was used for running simulations. On the other hand, the chosen mesh was enough complex to achieve reliable radio wave simulations results. Meshed models are illustrated in Figure (4).

Figure (4): Meshes of two wings models (a) Model NACA64A410 wing with inner structure
7- Running the Simulations
7.1- Setting Simulations Parameters
In this research two major simulation test cases were conducted:

- The influence of antennas positions upon the ZigBee performance.
- Investigation of the Zigbee WSN performance for aircraft engine sensors.

Actually, the number of test cases increased to four due to the fact that antennas position test case was carried out within three different simulation environments (three types of designed wings models). Consequently, the engine test case was only carried out within NACA64A410 wing model with an inner structure. Each simulation was conducted in two frequency ranges:

- From 100 MHz to 5 GHz frequency with 50 MHz step width (99 frequency samples)
- From 2.4 GHz to 2.48 GHz frequency with 5 MHz steps width (17 frequency samples).

Obtaining simulations in 100 - 5000 MHz range let find out what place was taken by the ZigBee ISM band in the coupling between antennas, the coupling is the S21 parameter estimation. The 2.4 -
2.48 GHz range represents 26 channels frequencies in the ISM band. For simulations environment the free space environment (vacuum) was chosen to run the simulations for radio wave propagation as a medium because in wing structures many types of medium exist such as: air, fuel and lubricants may have huge impact to radio waves propagation and their influences were not taken into account in these research objectives.

### 7.2- Antennas positioning case

To test the influences of antenna positions upon radio wave propagation, the used antenna model was characterised by the following features:

- Half-wave dipole structure with 62.5 mm wire length and 350 µm radius.
- Placement of antenna’s bottom edge on the lower wing plane Vertical orientation.
- Feeding input at antenna’s centre with value of 1 mW, 50 Ω feeding impedance.
- Each antenna was a transceiver.

The testing steps are as following:

1. Placement of 1st transceiver close to the wing root - representation of control device in aircraft cabin.
2. Putting 2nd transceiver at 1/4 wing length.
3. Running the simulation.
4. Putting 2nd transceiver at 1/2 wing length.
5. Running the simulation.
6. Putting 2nd transceiver at 3/4 wing length.
7. Running the simulation.
8. Putting 2nd transceiver close to wing tip.
9. Running the simulation.
This algorithm was repeated with the usage of different radio wave propagation environments shown in Figures (2) and (3), so this approach let research the influence of shape and the inner structure occurrence of the wing with varying antennas positions. The position of antennas was analogically for each antennas position test case (See Figures: (5), (6)).

Figure (5): Transceivers positions (coordinates point the position of antenna bottom end) – realistic NACA64A410 wing with inner structure

Figure (6): Transceivers positions (coordinates point the position of antenna bottom end) - Empty prismatic wing model without inner structure
7.3- Engine Simulation Test Case Description

In this case, the influence of multiple antennas appearance upon radio wave propagation within an aircraft wing cavity was researched. Seven transceivers represented wireless sensor network used to collect data from engines sensors. Six sensors nodes were placed approximately near 1/3 wing length. The location of the transceiver came out of most common engine mounting position (See Figure (7)) in transportation aero planes according to [11]. The position of bottom end of antennas is illustrated in Figure (8).

![Figure (7): Common positions of wing mounted engines](image-url)
8- Results

8-1 \( s_{21} \) Parameter Estimation

The magnitude of \( S21 \) parameter expresses the coupling between two ports (antennas), so it indicates the quality of connection link between these ports. The first common feature of all gathered results was the fact that the operational ISM band of the ZigBee standard appeared to be local minimum in the 100 MHz - 5GHz examined frequency range. The results of \( S21 \) are shown in figure (10).

![Figure (9): Transceivers positions near engine location](image)

![Figure (10): S21 Parameters Results](image)
The second joint characteristic which arose from the s-parameter estimation figures (11) and (12), shows that there is a cut-off frequency band oscillating between 100 MHz and 500MHz. Finally, the simulations proved that coupling between the transceivers in 2.4 - 2.348 GHz ISM band in all considered test cases were significantly below (up to -73 dB value) typical minimum value of the ZigBee SNR.

For that reason, the ZigBee performance is low, due to the fact that transmitted data between antennas will be undelivered. The obtained s-parameter meets expectations of the ZigBee SNR value in points when frequency is much bigger than 2.4 GHz (3 GHz - 5GHz) or much lower (vicinity of 500 MHz and 1250 MHz). In that case, different wireless technology should be examined in an aircraft environment application or plausible it will be needed to increase a number of the WSN nodes in wing structures. The simulation with usage different type of antenna (e.g. monopole) might be also considered.

8.2- The Influence of Antennas Positions

The position of antennas has enormous influence upon radio wave propagation. Especially, it can be observed in comparison between empty prismatic model and realistic NACA64A410 model with an inner structure. Figures: (11) and (12) illustrate the coupling between transceivers upon different antenna position for particular wing model. The simulation showed, in the wing cavity, coupling between ports are better when transceivers are far away in tested ZigBee ISM range (up to -10 dB in the complex wing model). The effect of this property may arise from high reflection and resonance effects from ribs or even only wing tip surface and wing shape.

The lowest coupling value as seen in figures (11) and (12) (-73 dB) characterizes 2nd transceiver position at 1/4 wing length in empty rectangular model and it occurs at 2.465 GHz frequency. The
lowest values at 1/4 wing length occurs also in (approx. -70 dB at 2.46 GHz) NACA64A410 the empty wing model. In the most complicated model the situation was different. The lowest values of the coupling appeared for the 2nd antenna located at half of the wing length as well as for 3/4 length.

For the 1st ZigBee channel the best (-30 dB) and the worst (-63) coupling between antennas appeared for 2nd transceiver position at 3/4 length within empty prismatic environment. It might be caused by the fact that resonances and reflections are much less in comparison to more complex shapes.

Figure( 11 ): Comparison of transceivers positions influence – empty prismatic wing module without inner structure (a): 100 – 5000 MHz band.
Figure (11): Comparison of transceivers positions influence – empty prismatic wing module without inner structure. (b): 2400 – 2480 MHz band.

Figure: (12): Comparison of transceivers positions influence- realistic NACA64A410 wing module with inner structure: (a): 100 – 5000 MHz band.
Figure: (12): Comparison of transceivers positions influence- realistic NACA64A410 wing module with inner structure: (b): 2400 – 2480 MHz band.

Table 2: Comparison of S21 Parameter Estimation in Antennas Position Test Case for 1st ZigBee channel

<table>
<thead>
<tr>
<th>1st Transceiver Number</th>
<th>2nd Transceiver Number</th>
<th>S21 Value [dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>-54.5885</td>
</tr>
<tr>
<td></td>
<td>3</td>
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<td>6</td>
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<td></td>
<td>7</td>
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<tr>
<td>6</td>
<td>7</td>
<td>-34.532</td>
</tr>
</tbody>
</table>

### 8.3- Hotspots of Radiation in External Wing Sur- faces

#### 8.3.1- The Influence of Wing’s Shape

In realistic as well as in empty wing shaped models, the current in external wing planes accumulated close to the trailing edge of the wing tip and also around the trailing edge of the wing kink. The accumulation of the current in these spots was mainly caused by a diffraction phenomenon occurred along sharp edges, which are the trailing edges. For that reason, the empty rectangular shape of the model did not accumulate the magnetic current – values close to zero. Furthermore, the magnetic one on external wing planes did not produce the electric current. In comparison to the wing shaped model, the order of magnitude was up to 8 times lower. Additionally, in the empty prism model, the current is more steadily decomposed on the external wing surfaces. It is caused by...
the fact that reflection in prismatic shaped cavities is lower than in more complex wing. The significant change of the wing shape (prism to aerofoil) changes the current value (decreases) as well as the location of the hotspots in external wing surfaces.

8.3.2- The Influence of Wing’s Inner Structure
An existence of an inner structure has huge impact upon the radiation in external wing surfaces. Its main effect was the current absorbency in the spars as well as in the ribs. For that reason, the magnetic strength in external wing surfaces are significantly higher than in NACA64A410 wing model with inner structures. The maximum value of the current was caused by the radiation of 2nd transceiver placement at 3/4 length of the wing in empty wing shaped model (367092 A/m). In this particular case, the maximum radiation was shifted about 70 cm from the wing tip. The location of the maximum current in external surfaces did not change with an inner structure occurrence. From that fact, it could be concluded that, the existence of the inner structure just only decreases the accumulation of the current in external surfaces rather than changes the location of the hotspots.

8.3.3- The Influence of Antennas Positions
The current distribution was also depended on localization of transceivers. The maximum current occurred when 2nd antenna was placed at 3/4 length of the wing. And also there is no significant difference between 2nd antenna placement at 1/4 wing length and at wing tip, especially in an empty NACA64A410 wing model. It could be explained by the fact of reflections from closing wing surfaces: wing root surface as well as wing tip surface.

8.3.4- The Influence of Multiple Antennas
When inside the realistic NACA64A410 wing model were put 7 nodes, which represented WSN for engine health management, the current distribution in external wing surface changed rapidly with
location of the transceivers. The maximum current characterized development by the 2nd antenna position (91720 A/m) and 5th transceiver location (88153 A/m). The lowest value of the current was caused by 1st antenna (6575 A/m). Magnetic field strength induced by 1/st antenna was absorbed by surrounding spars and 2nd and 5th antennas were sounded by the leading edge, two ribs and one surface of the spar, so in this case, reflection from these surfaces and also diffraction on holes in the ribs might cause the accumulation of the current in external surfaces.

8.4- Hotspots of Radiation in Inner Structure of the Wing

Planes for observation the magnetic field strength inside the wing were inserted into the wing structure as shown in Figure (13). As even empty wing cavity could be considered as a Faraday’s cage, some amount of the current might “escape” into space through the wing external surfaces. In many discussed cases, the magnetic field exists outside of the external wing contour. The hotspots of radiation have spherical referring to the horizontal planes and they are located along trailing edge close to wing king and wing tip.

8.4.1 The Influence of Wing’s Shape

The current distribution in horizontal as well as in vertical plane are much uniform than in other cases. Much more high values of the current occurred in the horizontal plane in the empty wing shaped model. It might be caused by the reflections of the radio waves from both upper and bottom external surfaces of the wing as well as wing tip surface (current value equaled to 1470 A/m when the 2nd antenna was close to the wing tip).

8.4.2- The Influence of Wing’s Inner Structure

Along both, vertical and horizontal planes it could be observed that an inner structure absorbs the magnetic field, so a value of the
current was higher in an empty NACA64A410 wing model. It was similar to phenomena, which occurred in external surfaces.

Figure (13): Location of planes, where magnetic strength field was calculated.
8.4.3- The Influence of Antennas Positions
Almost in all cases, the current distribution along vertical and horizontal planes is similar. The exception from this rule occurred when 2nd antenna was located at 1/4 wing length and close to the wing tip. In these two cases antennas were similarly close to root wing surface and wing tip surface, so the reflection from those surfaces had significant role in the radio wave propagation inside wing cavity. Consequently, the values of currents were maximal in these particular antenna locations.

8.4.4- The Influence of Multiple Antennas
All nodes of the simulated WSN for engine sensors generated magnetic field with maximal current accumulated around trailing edge near wing tip. In some cases it can be observed that, on horizontal plane there is also a hotspot of radiation near trailing edge of the wing kink. The 7th transceiver and the lowest current generated the biggest current on the vertical plane by the 1st antenna. The reason for that could be the current generated by the 1st transmitter fades after numerous radio wave reflections from root wing surface. Consequently, the current generated by the 7th antenna increased due to the diffraction and reflections originated from trailing edge vicinity.

9- Conclusion
The ZigBee performance of an aircraft environment has been overviewed and simulated. The designed models had different grade of complexity to let investigate the influence of the cavity shape upon radio wave propagation. After the meshing models, the simulations were carried out in these wing models to find its parameters. The simulations were run into two ranges – 100 - 5000 MHz and, 2400 - 2480 MHz. The analysis of the simulations covered coupling between the Zigbee antennas into consideration of different positions of the antenna. The simulation results were
stated during an examination of the wing and the wireless network model. S21 parameter estimation proved that the operational ISM band of the ZigBee standard appears to be a local minimum in the 100 MHz - 5GHz examined frequency range. In this case, the coupling between the antennas is very weak in 2.4 GHz bandwidth. In addition to the analysis of S21 parameter estimation showed that the coupling between the ZigBee antennas is much lower than expected typical minimal SNR value. This fact hinders the utilisation of the Zigbee WSN in highly reverberate environment such as wing cavity. The examination of the influence of wing shape as of the antennas positions and multiple antennas appearance at 2.405 GHz frequency (operational frequency of the 1st ZigBee channel in 2.4 GHz ISM band) proved that these factors have highly impact upon the Zigbee WSN performance. Particularly, the wing shape (mainly gradation of thickness along the length) caused resonance, which makes the coupling between nodes possible. This wing feature has the largest impact upon the performance of the ZigBee standard in wing cavities environment.

References


