A Review of Emerging Technologies in Antennas and Phased Arrays for Avionics Systems

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***Abstract*—**In recent years, research in aircraft avionics systems (i.e., radars and antennas) has grown revolutionary. Aircraft technology is experiencing an increasing inclination from all mechanical to all electrical aircraft, with the introduction of inhabitant air vehicles and drone taxis over the last few years. This develops an overriding need to summarize the history, latest trends, and future development in aircraft avionics research for a better understanding and development of new technologies in the domain of avionics systems. This paper focuses on the future trends in antennas and phased arrays for avionics systems. Along with the general overview of the future avionics trend, this work describes the review of around 50 high-quality research papers on aircraft communication systems. Electric-powered aircrafts have been a hot topic in the modern aircraft world. Electric aircrafts have supremacy over their conventional counterparts. Due to increased drone taxi and urban air mobility, fast and reliable communication is very important, so concepts of Broadband Integrated Digital Avionics Information Exchange Networks (B-IDAIENs) and Modular Avionics are being researched for better communication of future aircraft. A Ku-band phased array antenna based on a modular design can be used in a modular avionics system. Furthermore, integrated avionics is also emerging research in future avionics. The main focus of work in future avionics will be using integrated modular avionics and infra-red phased array antennas, which are discussed in detail in this paper. Other work such as reconfigurable antennas and optical communication, are also discussed in this paper. The future of modern aircraft avionics would be based on integrated modulated avionics and small artificial intelligence-based antennas. Optical and infrared communication will also replace microwave frequencies.

***Keywords*—**AI, avionics systems, communication, electric aircrafts, Infra-red, integrated avionics, modular avionics, phased array, reconfigurable antenna, UAVs.

I. Introduction

A. Earlier Developments in Aircraft Communication

THE aviation industry has seen much improvement lately. From the plane designed by the Wright brothers to now, everything has changed from small engine parts to the electrical circuitry present in the cockpit. With the advancement in technology, we are now shifting from all mechanical to all electric aircraft with more automation. Every aspect of an aircraft has seen refinement whether it is a design feature of an aircraft or the other items associated with it such as communication system and the airport network. Electric aircraft and drone taxis need fast and reliable communication not only within the internal aircraft circuitry, but also with other aircraft flying in their vicinity, to avoid collision and to carry on other flight operations. This review paper would mainly focus on the advancements in the avionics system of an aircraft and the communication network of an aircraft with the outside world using various antennas and radars. Improving the avionics system means the efficiency of the aircraft would also improve and the overall cost of flying would reduce significantly [1].

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In early times, Morse code was used as the main source of communication between the aircraft. It was mainly used to send wireless telegrams over the air to give or receive orders as WW1 was taking place [2]. Later, the first transmitter was made in 1906 by Reginald Aubrey Fessenden (1866-1932) in Massachusetts. It was mainly used as a transmitter for a rock musical band by using amplitude modulation (AM) [3]. Later at Blackman’s Point, Brant Rock, in the County of Plymouth Massachusetts, the first speech and music were transmitted to the sailing ships [4]. This is marked as the start of the new era in communication technology which would further be so much enhanced in the upcoming days.

In 1915, the first air to ground communication was established over some 20 miles by transmitting human voice rather than Morse code [5]. The war started afterwards and in 1938, Army Airways Communications System (AACS) was established for communication between troops. Point-to-point communication was developed between the army troops on the ground and the air which led to the development of many transmitter towers and antennas along major airports and airfields all over the United States of America [6].

The main surge in aircraft communication took place after the 1930s when radar communication was developed, which gave birth to modern communication. The competition between the United States and Soviet Union led to the development of the best technology available today [7]. The airborne radars using various types of antennas were developed later on in the 1950s which could map as much as 30 miles of an area [8]. Further improvements were made which are still in use today.

B. Phased Arrays

Phased array is a type of antenna which is most extensively used in the modern world and for aircraft communication. “A phased array usually means an electronically scanned array or a computer-controlled array of antennas which creates a beam of radio waves that can be electronically steered to point in different directions without moving the antenna” [9]. Phased arrays are used for both military and civilian purposes. Due to their versatility and ease of use, phased array antennas are the main choices in commercial and military aircraft.

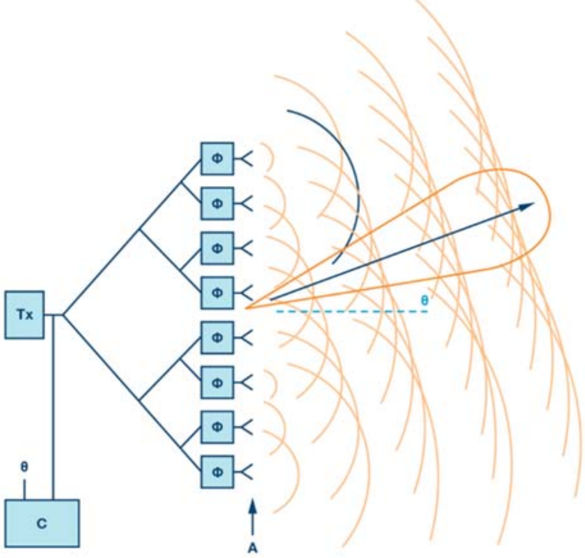

Fig. 1 Beam forming of phased array antenna [10]

In the past, mainly phased arrays were in form of tube passive arrays and solid-state active arrays, which use discrete and MMIC (Monolithic Microwave Integrated Circuit) technologies that have been deployed or are under development. At present, many novel and innovative ideas are being researched to develop new phased array antennas and radars [11]. Phased arrays are mainly of two types, passive and active arrays. In an active array, a transmit/receive module (TRM) is used at each element to provide amplitude and phase control. Active arrays provide added system capability and reliability but they did not receive extensive attention until the last 15 years because they were too complex and expensive. The central transmitter used in a conventional passive array is replaced by the distributed power amplifiers in each TRM. The radiation patterns of linear and planar-phased arrays are a function of each element's physical structure, its excitation, and the array lattice. The radiation pattern consists of main beam which is surrounded by small side lobes as modeled by the equation given ahead which helps with detection [12]. The equation the array factor is given by,

$$F_a(\theta,\emptyset) = \left[\sum_{-N_X}^{N_x} I_m e^{jm(kd_x \sin\theta\cos\emptyset - \alpha_x)}\right] \times \left[\sum_{-N_y}^{N_y} I_n e^{jn(kd_y \sin\theta\sin\emptyset - \alpha_y)}\right] \quad (1)$$

The performance characteristics of scanned arrays are easily determined using computer simulations, allowing for fast and inexpensive design [12].

II. EMF in Aircraft

EMF or electromagnetic radiation can pass through various elements in an aircraft and reach the cockpit and the avionics system. Moreover, EMF is also produced inside the cockpit by various circuitry present such as braids of wires as big as 0.2 mm which are commonly used for shielding. Other instruments such as transmitter and receiver antennas also contribute to the electromagnetic radiation throughout the aircraft. Now the aircraft's EMF is given by the Maxwell equation in the frequency domain,

$$\nabla\times\nabla\times E = k^2 E \quad (2)$$

where $k = 2\pi/\lambda$ and lambda is the wavelength of the outside EMF. The wavelength is most commonly in range of 10 cm to 100 m [13].

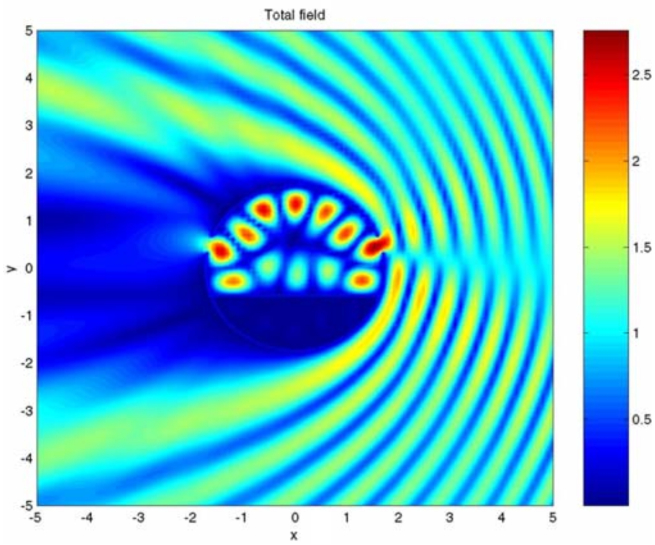

Fig. 2 EMF passing through the windows of an aircraft; this result is obtained using Multiscale modelling [13]

Normally, 4.2 to 4.4 GHz bands are allocated to aircraft as it is the most recommended band in accordance with Wireless Avionics Intra Communications or WAIC. It has shown that at this band of frequency, the radio interferences are not harmful [14]. For example, the EMF of Airbus A320 is modeled at 4 GHz using the large-scale finite-difference time-domain (FDTD) method. This analysis was carried out on a supercomputer and required more than 6 TB of memory. The transmitter antenna was placed 1 meter above the floor of the aircraft and the radiation field was modeled [15]. The results obtained from this simulation helps us in better understanding the spread of EMF from an aircraft and how we can make better use of it.

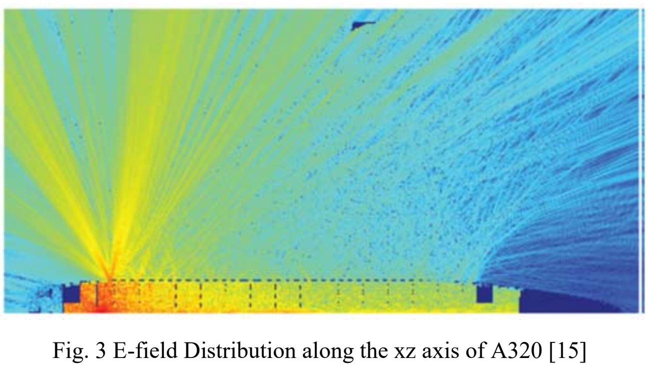

Fig. 3 E-field Distribution along the xz axis of A320 [15]

In Fig. 3, we can see the radiation pattern made by the antenna placed in the frontal part of the fuselage and how the EMF is spreading throughout the entire aircraft and to the outside world.

Aircraft has to fly through high EMF radiation environments and it is also necessary to protect the avionics inside of an aircraft from RF coupling through the outside interferences that the various instruments would be catching. The effect of RF coupling can be simulated by conducting various tests using mode-stirring techniques [16].

III. All Electric Aircraft

A. Overview

Electric powered aircrafts have been a hot topic of research in the modern world. They would not require any fuel and will be powered by electricity generated either by the solar panels on the aircraft itself or the charge stored in the batteries [17]. They can be hybrid as well and can run on fuel and batteries both. They can be powered by electric generators such as High Voltage Variable Frequency Starter Generator [18]. Electric aircrafts have many advantages over the conventional fuel breathing aircraft such as being environmentally friendly, less running cost, noise free and many others [19]. Overall, the all-electric aircraft has many benefits and in the upcoming future, nearly all aircraft will slowly be replaced by the electric-powered aircraft [20]. Electric drone taxis are already available in the market. Now many new avionics prospects with this are being researched which are listed below.

B. Broadband Communication

A new concept of Broadband Integrated Digital Avionics Information Exchange Networks (B-IDAIENs) is being researched for the better communication of the future aircraft. This would greatly improve the communication efficiency, flexibility and capacity as compared to the avionics buses which are currently used by most of the aircraft. It is believed that B-IDAIEN's would provide better real-time video and voice communication and better high or low speed data transmission in parallel communication. It would use N-wavelength transmitter and receiver arrays as they accomplish higher reliability in parallel communication using wavelength division multiplexing (WDM) [21]. Now the buses can be integrated together as well by using integrated modular avionics. The concept of modular avionics is explained in the next section. The communication between the different parts of the integrated modular system and others can be done by WDM and Full Duplex Switched Ethernet (AFDX). It will have high bandwidth and better connection. As AFDX does not provide any real physical transmission, together combined with WDM it overcomes this problem. The speed, cost and other aspects are greatly improved using this system [22].

C. Modular Avionics

Communication plays a vital role in deciding the combat abilities of a fighter aircraft. As technology is improving, modern customers demand the affordability and availability of new systems. A new idea is under development which is an open system concept for modular avionics. Modular avionics would have different blocks and avionics sensors enclosed in a box which would in return provide better interference with other electronic circuitry of the aircraft due to a tightly packed structure. This would also reduce the weight and maintenance would be easier as the blocks could be replaced easily without impacting other areas of the system. Special integrated sensors would be required to receive or send information using either one or an array of antennas which would be interfaced with the system at a baseband level. The cost is again the deciding factor and by using modular avionics, the cost would be significantly reduced [23]. A Ku-band phased array antenna based on a modular design can be used in modular avionics system [24]. It will have a frequency range from 12.5 GHz to 12.75 GHz. The main advantage of using this band of antenna would be the reduction of cost as phased arrays are quite cheap and better reception of signals for mobile avionics applications such as receiving multimedia. Another X-band antenna which works using modular technology is also being researched which would be in the shape of a cube. This antenna would be plug and play. This antenna can also be installed in array configuration and it will be used to communicate with satellites. Overall, this type of antenna shows good results in both receiving and transmission [25].

IV. Integrated Avionics

Integrated Avionics has been a major topic of research over the past few decades. Integration is the process of revolutionizing the design of an avionics system by integrating all of the avionics circuitry onto a chip [26]. Now integrated avionics has many advantages than the conventional avionics system such as being more efficient and better resource management [27]. We can have transition from federated avionics architectures to integrated modular avionics in the upcoming future as it holds more benefits. The transition requires resource management and taking care of open and closed systems [28]. Now if we come to the benefits of integrated modular avionics to our antenna design, it will drastically change the way we use antennas on the aircraft avionics system. Using integrated modular avionics, we would require to use integrated antennas which would greatly reduce the cost of antenna system on an aircraft. For example, using PAVE PACE integrated RF architecture would reduce not only the cost but also the weight and improve the overall connection [29]. Other new designs of antennas such as microstrip patch antenna can be developed for some super-fast aircraft. A cover can be created with invariable permittivity for the microstrip patch antenna and it would be useful with integrated avionics [30]. Another new technology being researched is the cheap contactless transactions for active phased array elements which would remove the need of coaxial cables and still give better results [31]. The cables can also be removed by using wireless fly-by technology. To achieve resource sharing, the antenna and RF components are integrated together along with the sensors and time triggered Ethernet is used to remove the cables [32]. High speed switching can be achieved using ARINC 664 and high-speed Ethernet, which is currently being used in integrated modular avionics, and further tests are being conducted to improve the switching speed [33]. A switchless communication network for integrated modular avionics can also be developed which can remove the problems caused by switches by using a distributed network system [34]. The US Airforce has been investing heavily in integrated avionics due to its benefits of cost reduction and the dynamic reconfigurability of integrated blocks. In the future, even those aircraft which are not currently using integrated avionics would be upgraded with it and it will reduce the size of antennas used in the aircraft [35].

V. Infra-red Phased Arrays

The phased arrays have been widely used for both military and civilian purposes. As the era advances, new techniques, such as IR imaging using phased arrays, are being developed. The main advantage of using IR is that it would improve readiness and the cost of phased arrays. It has been partially used on aircrafts such as F-15 but was never fully deployed. The main aim is to show how we can fully achieve IR imaging using phased arrays and that it would greatly improve the avionics of an aircraft [36]. To improve it, we can perform several methods. Antenna phasing at 10.6 micrometer wavelength can be achieved by using coplanar strip lines to interconnect the antennas. This will preserve the individual IR frequency and later they are all summed up at a common bolometric load. The maximum response depends on the current contribution from each antenna. Adding more antennas would result in a narrower beam [37]. A 2D, highly directive and very efficient infra-red transmission and reception can be established by using leaky-wave infra-red phased array [38]. Once the propagation loss in the transmission line is minimized, it results in better angle resolution for the IR phased arrays [39]. We can use Graphene layer on the resonator to achieve binary beam switching capability of the reflect-array. This will result in better scanning and higher beamwidth [40]. Another technique that is used for beamwidth switching in IR phased arrays is by using liquid crystals. An electric field is applied to the liquid crystal material, which changes the index of refraction, thus resulting in a change in the beam direction and width [58]. Infra-red phased arrays can also be used for radar applications as they have better scanning abilities as compared to traditional ones [41].

VI. Further Developments

A. Optical Communication

Optical communication in Avionics is also being researched. The main advantage of using optical communication is the cost, flexibility and being modular. To use optical communication, we require an optoelectronic transmitter and receiver and some circuitry to achieve the communication [42]. Optical phased arrays for lasers are also being in development. This type of phased array will use array of liquid-crystal-based optical phase shifters. The results are successfully achieved from green to long range infra-red. The advantage of using this phased array is the high pointing accuracy and the reduction of size as compared to others [43]. The Gigabit fiber optic transceiver technology is also being researched to be used in some aircraft avionics [44]. Bi-Directional fiber optic transceivers can also be used for avionics applications. It is a novel design which would be immune to all kinds of noise and thus it will be able to carry out any range of microwave frequencies [45]. It will also have the lowest cost as it is made of silicon which is very cheap.

TABLE I
Comparison between Microwave and Infra-Red Phased Arrays, Showing Advantages and Disadvantages

Attribute	Microwave Phased Arrays	IR Phased Arrays
Cost	Relatively lower cost	Improved readiness and cost as compared [36].
Interconnectivity	Interconnectivity using coaxial cables or waveguides	Coplanar strip lines are used for interconnectivity [37].
Beamwidth	Wide beamwidth	Preserves individual frequencies but results in narrower beamwidth with more antennas [37].
Directivity	Moderate directivity	Highly directive with efficient transmission and reception [38].
Angle resolution	Limited angle resolution	Better angle resolution that can be further improved by minimizing propagation loss in transmission lines. [39].
Beam switching capability	Achieved by electronically steering the beam.	Enabled by continuous graphene or by using liquid crystals and manipulating the refractive index. Both are effective yet a bit expensive [40], [58].
Radar applications	Limited scanning abilities	Better scanning abilities for radar applications [41].

B. Moving towards Automation and AI

AI or Artificial Intelligence-based antennas can also be manufactured as they are currently under research for future avionics technology. AI antennas can work by using neural network algorithms [46]. An AI antenna will decide on itself the best antenna configuration for different purposes and how to achieve maximum directivity, beamwidth and other aspects on its own. It can be combined with the upcoming 5G technology and hence can be fully automated [47]. Shape blending can also be used to achieve antenna automation [48].

C. Reconfigurable Antennas

Reconfigurable antennas are such antennas whose frequency and radiation pattern can be altered. Thus, a reconfigurable antenna is not frequency limited and can be used on a wide range of frequencies [49]. They can be either controlled manually by any software or fully automated. Some antennas can alter the geometry so that they can achieve the desired frequency and radiation pattern [50]. As now everything is moving towards automation and in the future, the aircraft avionics will also be connected using 5G technology [51]. The 5G would require reconfigurable antennas to meet their expectations. The main advantage of using them over other types of antennas is their better performance for 5G [52]. Reconfigurable antennas such as a Bow-Tie can also be used for other applications including Bluetooth, WLAN and WiMAX (Worldwide Interoperability for Microwave Access) [53]. Multiband, dual polarization dual antennas for beam reconfigurable antenna system can also be used for indoor purposes such as LTE and WLAN [54]. Millimeter-wave phased arrays are being brought in 5G technology due to their better performance and ability to carry multiple users at high data rates utilizing high bandwidths. They are not only compact but also power efficient [55]. Furthermore, reconfigurable circular disk antenna also provides better coverage for WiMAX/WIFI with good gains and less losses [56]. AI can also be combined with reconfigurable antennas. Results have shown that AI-based reconfigurable array coupling proved to be a better alternative and more efficient than a traditional experience-driven design method [57].

VII. Conclusion

In conclusion, many future trends are being developed for antennas and phased arrays to be used for avionics systems. From broadband communication to reconfigurable 5G antennas, many new novel ideas are being tested. In the future, avionics of all aircraft would be based on integrated modular avionics and small AI-based microstrip patch antennas will be favorable. A shift from microwave frequencies to infra-red and optical communication will be observed.

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