Chapter

Design of an Ad Hoc Mesh Network for Aircrafts

Ichi Kanaya and Eri Itoh

Abstract

This article reports an exploration of the information flow among aircrafts and describes a novel digital communication protocol which uses ad hoc mesh networking technologies. The proposed process may be operated utilizing current aircraft hardware and accomplishes very dependable interaction with a quick time period (a couple of tens of seconds). Simulations check that over 200 [octet] of information is usually shared with 98% of the aircraft inside a chosen region.

Keywords: wireless communication, ad hoc network, mesh network, internet protocol, air traffic management

1. Introduction

Communications among aircrafts (air to air) and between an aircraft and the ground control (air to ground) play a crucial part in the secure operation of the aviation business. Flight Deck Interval Management (FIM) that exchanges place as well as altitude information straight between planes is a major engineering for Continuous Descent Operation (CDO), resulting in extremely effective aircraft operations. Underneath CDO, arrival plane descends at a continuous velocity to the runway at a state close to idling; current study results have shown the power effectiveness of this particular strategy [1, 2].

Conventional analysis suggests that the Aircraft Surveillance Applications System (ASAS) may well not have the ability to deal with the projected intense increase in the variety of the plane until the authors are able to conquer the bottleneck of information sharing involving aircrafts. ASAS enables the surveillance of adjacent traffic flow in the environment with the traditional Automatic Dependent Surveillance Broadcast (ADS-B), which are only able to process incredibly limited quantities of info, which means that innovative correspondence is not possible [3].

Even though satellite and the ground-based internet for aircraft usually do not address whole routes, they offer non-mission-critical internet services to passengers. Additionally, they usually need the assembly of a new antenna on the plane.

In this analysis, the authors think about the setup of an ad hoc mesh system which employs the current aircraft communication tools almost as practical and will discuss adequate information for the FIM. This proposal is dependent on the concept that the existing aircraft facilities are untouched, making it possible for a system to be recognized without renovating the outside of the plane. Additionally, the proposed technique is powerful against unexpected accidents including equipment breakdown, since it does not need a predesigned topology and can transmit data redundantly throughout the mesh network.

This concept is complementary to the standard internet technology for aircraft like satellite web. It's potential to run web-based FIM even once the plane is outside of the coverage of internet services.

2. Related work

The authors discuss about connected researches on candidates for inter-aircraft computer networks in terms of the Open Systems Interconnection (OSI) reference model. The authors likewise outline the current radio equipment found in a regular aircraft.

2.1 Physical and datalink layers

The authors discuss IEEE 802.11 (Wi-Fi), IEEE 802.16 m (WiMAX), and IEEE 802.15.4 and IEEE 802.22 that are standardized by the IEEE 802 standardization committee for local area networks (LAN) and metropolitan area networks (MAN). The authors subsequently present an overview of satellite internet as well as the ground-based internet. Lastly, the authors are going to touch on the communication technologies presently used in the plane.

IEEE 802.11a/g/n/ac (also known as Wi-Fi) is a physical and datalink layer protocol that uses 2.4–2.5, 4.9–5.0, 5.03–5.091, 5.15–5.35, and 5.47–5.725 GHz. The modulation is performed by orthogonal frequency-division multiplexing (OFDM) that uses orthogonal subcarriers [4–6].

IEEE 802.16 m (also known as WiMAX) is a physical/datalink layer protocol that uses wireless networking for communication over a wider space than the IEEE 802.11a/g/n/ac series. It often uses 2.575–2.645 GHz UHF band and OFDM [7, 8].

Long-Term Evolution (LTE) is a standard for mobile phones. In Japan roughly 0.7–1.7 GHz (UHF band) is employed. It uses quadrature phase-shift keying (QPSK) over OFDM in every subcarrier [9–11].

IEEE 802.15.4 and IEEE 802.22 are less famous than the above three protocols. IEEE 802.15.4 is a physical/datalink layer protocol for short-range wireless communication which uses 868.0–868.8, 902–928 MHz, or 2.4000–2.4835 GHz and direct-sequence spread spectrum (DSSS) or offset quadrature phase-shift keying (OQPSK). IEEE 802.15.4 is best widely known as Zigbee wireless network protocol. IEEE 802.22 is a standard for wireless regional space networks using white areas within the TV broadcast bands [12].

Satellite net services are primarily provided by geostationary satellites, although some are provided by satellite constellations who relay communications via many satellites. As fixed satellites do not handle the polar regions, therefore the communication coverage of theirs is restricted.

Since satellite constellations are able to work with low-earth-orbit satellites, the correspondence latency is smaller than within the net service provided by fixed satellites. Because the places of those satellites are completely dynamical, an omnidirectional antenna is usually required, and far additional power is required than for communication with fixed satellites [13, 14].

The authors here shortly discuss about ground-based aircraft internet, aircraft-based internet, and latest developments in long-distance and low-speed network engineering for the Internet of Things (IoT).

References [15–25] show other popular wide-area network technologies.

A voice communication channel using 118.0–136.975 MHz (VHF) is also used. The audio uses amplitude modulation (AM).

2.2 Network layer

In the network layer protocol, the Internet Protocol (IP) is the factual standard whenever the datalink level has enough bandwidth. Based on the IP, the Space Communications Protocol Specifications (SCPS) may also be used when the band is extremely narrow, like for communication between the earth and other planets [26, 27].

2.3 Transport layer and above

It's typical for the transport layer to ensure end-to-end communication. In networks based on the IP for the network layer, the Transmission Control Protocol (TCP) is often used for the transport layer [28]. Networks which do not make use of IP for the network layer, or networks which use IP but do not use TCP for the transport layer, occasionally have the own error-correction mechanism of theirs in the transport layer [29, 30].

The authors do not go over the session layer (or higher layers), as they are not the topic of the research.

3. Design of networking protocol

In the prior section, the authors summarized the conventional wireless network technologies. They're, nonetheless, unsatisfactory due to the constraints of the conventional aircrafts.

IEEE 802.11, IEEE 802.15.4, IEEE 802.16 m, and LTE will need the aircrafts to be engineered with freshly installed antennas and are probably jammed by high-speed movement and may experience radio interference since they are acting secondary modulation by OFDM.

As satellite internet utilizing geostationary satellites does not handle the polar regions, it cannot be put on to aircraft traveling near the North Pole. Furthermore, satellite internet utilizing satellite constellations necessitates broadcasting communication among the satellites, which is technically complicated.

Air-based internet and ground-based internet aren't ideal for FIM because the coverage area of theirs is limited.

Long-distance, low-speed networks (excluding LoRa) aren't ideal for FIM, because interaction with mobile vehicles is not taken into consideration in the design of theirs.

Consequently, the authors have created a brand new low-speed (1–10 kbps) wireless communication technology to allow the inter-aircraft flow of information. The authors assume that conventional wireless communications are used by the aircraft in the physical layer and the datalink layer for the best backward compatibility with existing aircrafts.

The authors present the following communication protocol and then verify the effectiveness of the protocol by simulations.

3.1 Physical layer

The authors assume narrowband wireless communication in the physical layer. In order to share the antenna with SSR [31, 32] the authors utilize the UHF band as well as frequency modulation (FM) that is ideal for digital signals, and they have high noise tolerance.

In thought of the practicableness of implementing this specific protocol on typical aircraft, the authors use precisely the same band as SSR (i.e., the UHF band) to enable the potential for diverting the SSR antenna.

As the current SSR uses a straightforward pulse-based communication protocol, the communication band is incredibly narrow. Thus, a bandwidth of roughly 10 kHz with adjacent frequency as being a carrier is available. The authors consider FM for the noise tolerance at this layer. Generally, AM is utilized for the lower selectivity of voice communication channels in aircraft communication, but as this proposal is restricted to digital communication, FM is adopted since it is more reluctant to interference compared to AM.

3.2 Datalink layer

The datalink layer encodes/decodes the data we send/receive with metadata including data sender, time code, etc. These packed data are referred to as the packets.

Permit the size of the packet at the season of exchange from the datalink layer to the physical layer be near 256 [octet]. As the littlest metadata, the authors incorporate a "magic" code up to 4 [octet] specifying the character of the packet, a time code (4 [octet]), and a code of the aircraft (4 [octet]). By considering these headers, 240 [octet] is left inside the datagram. Expecting that 2 kbps is offered as the channel of the datalink layer, it will take 1 s to transmit a solitary packet. The transmission capacity of 2 kbps could be feasible.

In detail, aircraft code (4 [octet]) contains the source aircraft code. A unique number for every aircraft must be allocated. The body (240 [octet]), followed by error-detection code, contains data body. The error-detection code (4 [octet]) contains error detection. CRC-32, which inspects the cyclic redundancy check, is used.

Packets having errors and packets older than a planned threshold are discarded. To scale back the load on the network layer, it manages "time to live" of the packet.

3.3 Network layer

The network layer encodes/decodes the sent/received data by wrapping/unwrapping the datalink packet. Dropping any irregular data is done in the network layer. If there are not any irregularities, the data is passed to the upper layer, that is, the transport layer. If needed, the received data is retransmitted. A signal body of the transport layer is named a datagram.

The datagram includes a code (up to 4 [octet]) stating the character of the datagram, a destination aircraft code (4 [octet]), a source aircraft code (4 [octet]), and a time code (4 [octet]). The size of the user space of the datagram is 224 [octet].

3.4 Transport layer

In contrast to the internet, it's really hard to assure end-to-end data transmission in aircraft communication. Therefore, the transport layer does not handle the end-to-end connection feature, that's characteristic of TCP, like data retransmission requests. Yet, a comparatively powerful error-correction capability is enforced to the transport layer. The Reed-Solomon (RS) code is thought to be the promising candidate. When three datagrams are transmitted together with error-correction signals distributed in four datagrams, the typical quantity of data per datagram is 168 [octet].

The Reed-Solomon code, which is a more practical error-correction function than the cyclic redundancy check (CRC), is enforced within the transport layer. If three datagrams are coupled with the error-correction signal and, as a result, distributed to four datagrams to be transmitted, 168 [octets] per datagram are allotted to the implementer.

4. Feasibility study of physical, datalink, and network layers

In order to confirm the feasibility of the protocol discussed in the prior section, the authors developed the model described below and conducted a simulation experiment.

Assume that N aircrafts a_i are existing at positions p_i, respectively. Position p_i may or may not be a three-dimensional orthonormal coordinate system. The primary point in this discussion is that the distance $p_i - p_j \vee$ between position p_i and position p_j is defined.

Let x_{ij} be the information the authors want to send to aircraft a_j from aircraft a_i. The information received by aircraft a_j is, nonetheless, different from x_{ij}—the authors denote it as y_{ij}.

When there's no error in the communication route, the information x_{ij} originating from aircraft a_i corresponds to y_j received by aircraft a_j. This can be described as

$$y_j = U_i x_{ij} \tag{1}$$

Let us denote the transmission rate of the communication route from aircraft a_i to aircraft a_j by c_{ij}. The transmission rate c_{ij} refers to the packet data transmitted by aircraft a_i that is actually received by aircraft a_j, that is, the probability of correct information transmission. Let c_{ij} be a function of position p_i and position p_j. That is, $c_{ij} = e(p_i, p_j)$. In wireless communication, we can reasonably assume that

$$c_{ij} = k \, \varepsilon^{-K|p_i - p_j|^2} \tag{2}$$

for some constants k, K. These parameters may be changed according to the results of experiments. In this report, the authors adopt Eq. (2) as the transmission rate c_{ij}.

Taking the transmission rate into account, Eq. (1) is modified to

$$y_j = U_i c_{ij} x_{ij} \tag{3}$$

Until now, the authors have dealt with only one-to-one communication from aircraft a_i to a_j, but we can consider another aircraft a_k relaying the communication described by x_{ij}. When the information that aircraft a_k receives and retransmits is z_k, where $z_k = _{ij} c_{ik} x_{ij}$, there would be an explosive increase in the amount of data if the authors do not use an artificial attenuation (decay) term d_{ijk}, as in

$$z_k = U_{ij} c_{ik} d_{ij} k x_{ij}. \tag{4}$$

Here, the attenuation term d_{ijk} denotes the probability of intentionally discarding the packet during the packet relay. Finally, the equation that takes the relay into consideration has the form

$$y_j = U_i c_{ij}(x_{ij} \cup z_{ij}). \tag{5}$$

In this report, to statistically investigate the arrival rate of data based on Eqs. (4) and (5), the authors performed computer simulation with the following parameters:

Airspace. Three-dimensional orthonormal space. It is a cube whose vertexes are (0, 0, 0)-(0, 0, 1)-(0, 1, 0)-(0, 1, 1)-(1, 0, 0)-(1, 0, 1)-(1, 1, 0)-(1, 1, 1). The units are arbitrary.

Time. The simulation is performed between 0 and 100 s with a time step of 1 s.

Number of aircraft. 1000 aircraft are randomly placed in the airspace.

Probability of successful communication. The probability of the successful communication is based on Eq. (2) according to the interval between the aircrafts. However, the authors set $k = 1$ and simulate K as $K \in \{0.1, 0.316, 1\}$. **Figure 1** shows the probability of success depending on the interval for each parameter.

For every simulation, the authors transmitted data from aircraft a_{999} to a_0 in each time step. If the data did not reach a_0 in a single time step, and if they reached a_n where $n \neq 0$, then a_n attempted to send the data to a_0 in the next time step.

Theoretically, the attenuation term d_{ijk} in Eq. (4) must be equal to or less than 1, and the authors assumed that $d_{ijk} = 1$ in the simulations to clarify the experimental results.

The authors have done the following two investigations.

Simulation 1. Investigate the degree of data transmission per time step using multi-hop communication via neighboring aircraft wherever the communication path is unstable.

Simulation 2. Investigate the entire range of hops for every time step using multi-hop communication via neighboring aircraft wherever the communication path is unstable.

5. Experimental results

Figure 1 shows results of Simulation 1. **Figures 2** and **3** show the results of Simulation 2.

In **Figure 2**, the horizontal axis represents time steps, and the vertical axis represents the amount of aircraft (maximum 1000). The blue curve shows the case of $K = 0.1$, the green curve shows the case of $K = 0.316$, and the yellow curve shows the case of $K = 1$. All curves were plotted under the condition of $k = 1$.

Typical values of **Figure 2** are picked up in **Table 1**. Time steps 1, 30, and 60 correspond to 1, 30, and 60 s after the start of the communication, respectively.

The horizontal axis and the vertical axis of **Figure 3** represent generations and the overall range of hops needed for data transmission, respectively. The blue curve shows the case of $K = 0.1$, the green curve shows the case of $K = 0.316$, and the yellow shows the case of $K = 1$ under the condition of $k = 1$ in Eq. (2).
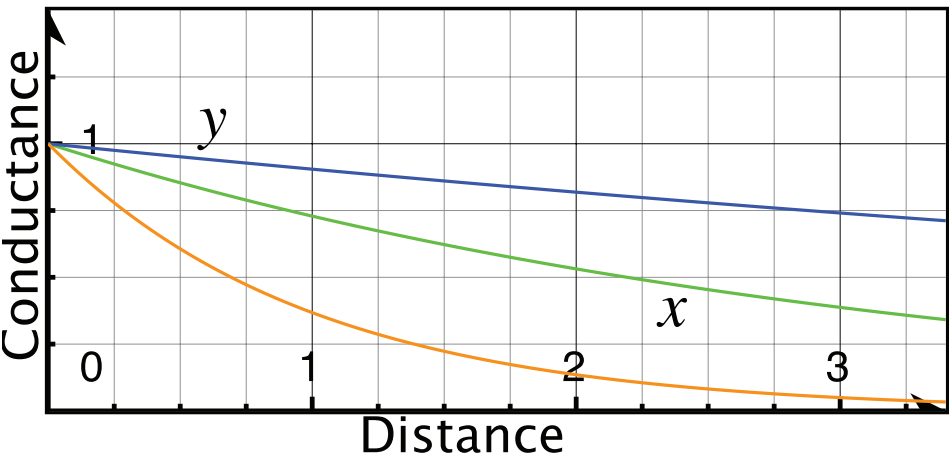

Figure 1.
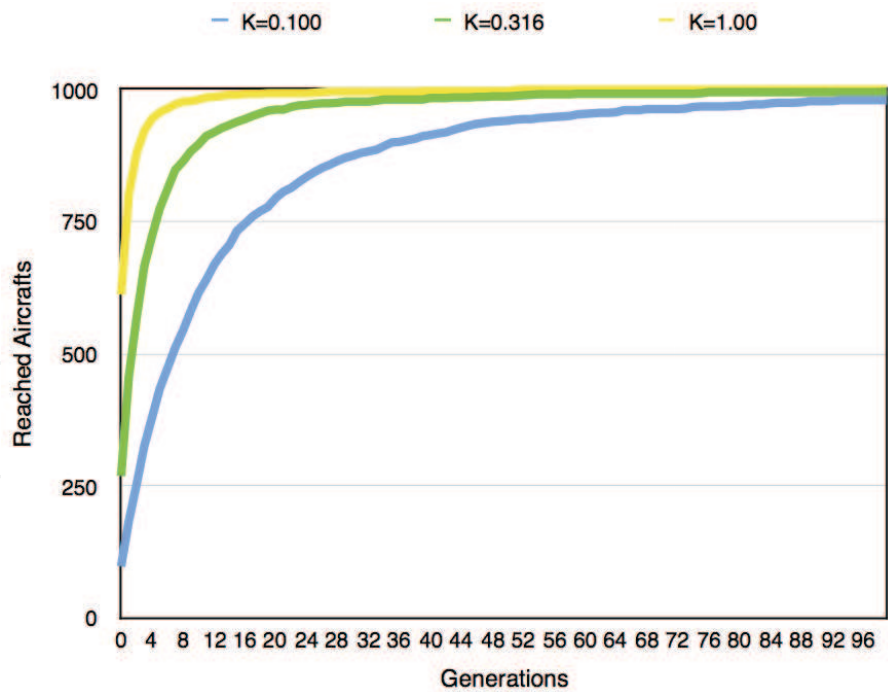*Simulation parameters (yellow, K = 0.1; green, K = 0.316; blue, K = 1).*
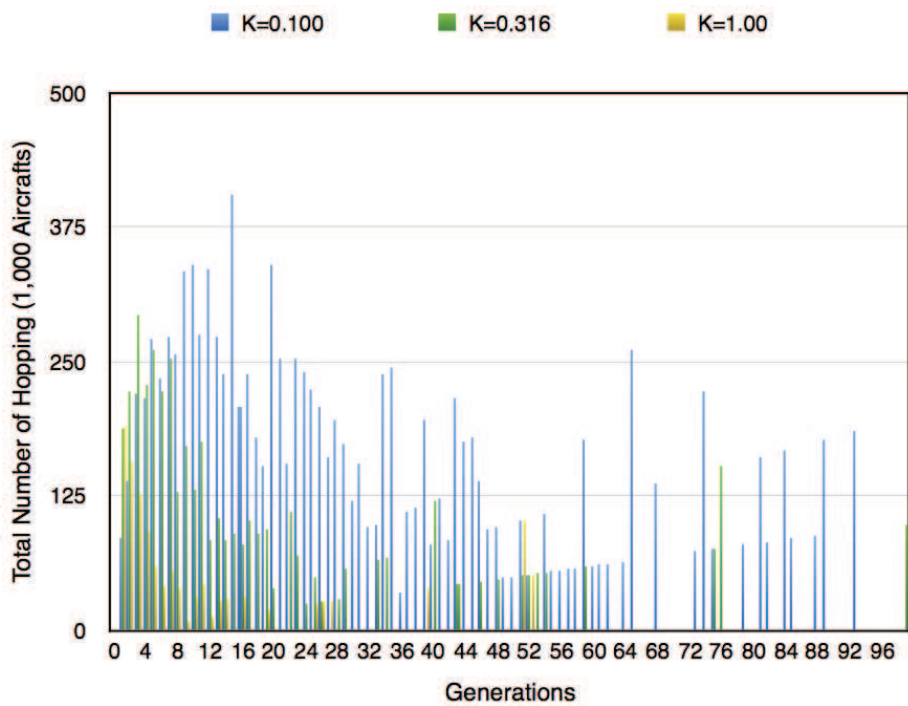
Figure 2.
Number of aircraft reached.

Figure 3.
Number of hops.

K	Generation 1	Generation 30	Generation 60
0.1	98	871	953
0.316	269	977	992
1	612	996	1000

Table 1.
Velocity of the spread of shared information.

6. Discussion

Simulation 1 under the condition of $K = 0.316$ shows that 97.7% of information is effectively transmitted by time step 30 (which means 30 s after the start of the communication). If we remind $\varepsilon^{-0.316} = 0.729$, we can say that the theoretical arrival rate of information with a distance of one in this model is 72.9%, while by this method, the rate can be improved to 97.7% (meaning 134% improvement) within 30 s, and this improvement can be achieved without controlling intervals of the aircrafts.

By the outcomes of Simulation 2, the total amount of hops necessary for information transmission is likely to decrease with a rise in the quantity of time steps. In this particular operation, its anticipated attenuation term d_{ijk} is set to less than 1, which means that attenuation is intentionally performed.

As discussed above, even in a communication environment with extremely small reliability, it's apparent that highly dependable communication is possible through the dispersed nature of the aircrafts in the airspace. Under the circumstances of this particular simulation, 97.7% of information was correctly shared among the aircrafts with 30 s of interaction. As the datagram size is no more than 224 [octet], aside from error correction in the transport layer, the data rate under a guaranteed transmission rate of 98% is approximately 60 bit/s in the worst case. (In the very best situation, the theoretical value is approximately 1.8 kbit/s).

Even though this appears to be an incredibly narrow communication band for contemporary wireless communication, it's a feasible numerical value for mission-critical inter-aircraft. For communication which is not mission critical, we are able to consider satellite internet as a complementary protocol.

7. Conclusion

In this article, the authors reported an investigation of the information flow among aircrafts and proposed a new digital communication protocol which uses ad hoc mesh network technologies. The authors illustrated the proposed protocol could be operated utilizing conventional aircraft hardware and will accomplish extremely dependable interaction with a very short time period (a couple of tens of seconds). The simulations supported the strength of the suggested protocol.

If the ad hoc mesh system introduced in this article will come into reality, the application will cover not only CDO but also the autonomous management of associate adjacent craft. Moreover, computer networks that will manage ultrahigh-speed nodes like aircraft would contribute to conventional mobile digital networks that are actively studied.

Acknowledgements

A. Simulation program

The simulation program used in this report is posted at https://github.com/kanaya. This program works with the Scheme interpreter (R5RS conforming or higher).

Author details

Ichi Kanaya[1]* and Eri Itoh[2]

1 The University of Nagasaki, Nagasaki, Japan

2 Electronic Navigation Research Institute, Tokyo, Japan

*Address all correspondence to: kanaya@pineapple.cc

IntechOpen

References

[1] Kanaya I. Proposal of inter-aircraft mesh computer network. Research Report. Japan: Electronic Navigation Research Institute, ENRI; 2016

[2] Itoh E, Brown M, Wickramasinghe N, Fukushima S. Future arrival management collaborating with trajectory-based operations. In: Air Traffic Management and Systems II. Germany: Springer; 2017

[3] Richards WR, O'Brien K, Miller DC. New air Traf surveillance technology. Aero Boeing. 2010;**02**:7-14

[4] Reid NP, Seide R. Wi-Fi (802.11) Network Handbook. USA: Osborne Networking; 2002. ISBN: 978-0072226232

[5] LitePoint. IEEE 802.11ac: What Does it Mean for Test? LitePoint Whitepaper. 2013

[6] IEEE Standard Association. IEEE Standard for local and metropolitan area networks Part 15.4: Low-Rate Wireless Personal Area Networks (LP-WPANs). IEEE Computer Society; 2011

[7] Fazel K, Kaiser S. Multi-Carrier and Spread Spectrum Systems: From OFDM and MC-CDMA to LTE and WiMAX. 2nd ed. USA: John Wiley & Sons; 2008. ISBN: 978-0-470-99821-2

[8] Richardson M, Ryan PS. WiMAX: Opportunity or Hype? ITERA; 2006. Available from: https://ssrn.com/abstract=892260

[9] Sesia S, Baker M, Toufik I. LTE: The UMTS Long Term Evolution: From Theory to Practice. USA: Wiley; 2011

[10] Dahlman E, Ekstrom H, Furuskar A, Karlsson J, Meyer M, Parkvall S, et al. The long-term evolution of 3G. Ericsson Review, No. 02; 2005

[11] Alcatel-Lucent. Using air-to-ground LTE for in-flight ultra-broadband. Alcatel-Lucent Strategic White Paper. Alcatel-Lucent; 2015

[12] Mody AN. IEEE 802.22 Wireless Regional Area Networks—Enabling Rural Broadband Wireless Access Using Cognitive Radio Technology. IEEE; 2010

[13] Walker JG. Satellite constellations. Journal of the British Interplanetary Society. 1984;**37**:559-571

[14] Ballard AH. Rosette constellations of earth satellites. IEEE Transactions on Aerospace and Electronic Systems. 1980;**16**(5):656-673

[15] Stotts LB, Plasson N, Martin TW. Progress towards reliable free-space optical networks. In: Military Communications Conference (MILCOM) 2011; IEEE; 2011. DOI: 10.1109/MILCOM.2011.6127559

[16] Gogo. Gogo ATG-4: What is it, and how does it work? Gogo Press Release; 2014. Available from: https://concourse.gogoair.com/gogo-atg-4-work/ [Accessed: 25 July 2017]

[17] Thompson P. How In-Flight WiFi Works And Why It Should Get Better; Jalopnik; Issue of 20/6/14; 2014. Available from: https://bit.ly/2eJpBy6 [Accessed: 25 July 2017]

[18] Anthony S. DARPA begins work on 100Gbps wireless tech with 120-mile range; Extreme Tech. Issue of 17/12/2012. Available from: https://bit.ly/2uUijh8 [Accessed: 25 July 2017]

[19] Miura R, Adachi F, Tada M, Yonemoto N, Watanabe S. R&D on Cooperative Technologies between Unmanned Aircraft Systems (UAS)-Based Wireless Relay Systems and

Terrestrial Networks with Frequency Sharing; System of Radio Use. Japan: Ministry of Internal Affairs and Communications; 2016

[20] Metz C. Inside Facebook's First Efforts to Rain Internet from The Sky. Wired; 2016

[21] Massemin E. Internet des objets, Ludovic Le Moan (Sigfox) lance l'IoT Valley a Labage; La Tribune Toulouse; Issue of 22/05/2012

[22] Kalfus R, Hegr T. Ultra narrow band radio technology in high-density built-up areas. In: Information and Software Technologies: 22nd Int'l Conf., ICIST 2016; October 13-15, 2016; Druskininkai, Lithuania: Proc., Springer; 2016

[23] EETimes Japan. Sony presented LPWA which communicated over 100km [in Japanese], EETimes Japan; Issue of 9/6/2017. Available from: https://bit.ly/2vDjjnI [Accessed: 25 July 2017]

[24] Prajzler V. LORA, LORAWAN AND LORIOT, LORIOT AG; 2015. Available from: https://bit.ly/2tV6KCp [Accessed: 25 July 2017]

[25] Svetlana G. 3GPP Low power wide area technologies. GSMA White Paper. GSMA; 2016. pp. 49

[26] Siyan KS. Inside TCP/IP. 3rd ed. USA: ACM; 1997. ISBN: 1562057146

[27] Gislason D. Zigbee Wireless Networking. Netherlands: Elsevier; 2008. ISBN: 9780080558622

[28] Kevin R, Fall W, Stevens R. TCP/IP Illustrated, Vol. 1. The Protocols. 2nd ed. USA: Addison-Wesley; 2014. ISBN: 978-9332535954

[29] Internet Engineering Task Force: RFC768. Available from: https://tools.ietf.org/html/rfc768

[30] Internet Engineering Task Force: RFC3550. Available from: https://tools.ietf.org/html/rfc3550

[31] Kayton M, Fried WR. Avionics Navigation Systems. 2nd ed. USA: John Wiley & Sons; 1997. ISBN: 0-471-54795-6

[32] Shipley R. Secondary surveillance radar in ATC systems: A description of the advantages and implications to the controller of the introduction of SSR facilities. Aircraft Engineering and Aerospace Technology. 1971;**43, 1**:20-21