Performance analysis of Cooperative Schemes for Wireless Sensor Network of Aircraft

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***Abstract*—In this paper, the wireless communication channels of the aircraft environment are investigated and total energy consumption, throughput metrics are analyzed by non-cooperative schemes which are single-hop, multi-hop, and cooperative relaying schemes which are Amplify and Forward(AF), Decode and Forward(DF), Incremental Decode and Forward(IDF), Incremental Amplify, Forward(IAF) to compare each performance. In case of the channel model, path-loss, large-scale fading, and small-scale fading channels are modeled by referring experimental parameters of ITU(International Telecommunication Union) report, which is measured in the aircraft between inter-cabin and inter-cabin and between inter-cabin and a wing. When the total energy consumption and throughput performance are analyzed by using six schemes, the incremental cooperative schemes outperform the other schemes in terms of energy consumption and throughput.**

Keywords:Cooperative Relaying, Channel Model, Avionics Intra-Communication, Wireless Sensor Network.

I. Introduction

According to the development of science and technology, aircraft facilities and electronic equipment have been advanced. Conventional electronic equipment of an aircraft is connected by wire to communicate between systems. This has a major disadvantage and may lead to potential problems depending on the scale of the aircraft, therefore another communication method needs to complement or replace existing wire communication. For example, in the case of large-sized aircraft more than 40,000 sensor nodes are deployed, and in medium-sized aircraft more than 6,000 sensor nodes are deployed. This means that each sensor node must be connected by wire one by one, so the weight of the airplane increases proportionally as the number of sensor nodes increases. According to this, the cost of the installed wire is considerable, and maintenance costs are regularly incurred [1], [2], [3].

Wireless communication performance in the aircraft can be degraded due to the harsh environment, such as lightning, snowing. In addition, through a lot of antennae for Automatic Dependent Surveillance-Broadcast(ADS-B), Aircraft Communications Addressing and Reporting System(ACARS), Airbone Satellite Communications(SATCOM), etc. interference can happen. So, To apply reliable wireless communication among sensors of the aircraft which are connected by wires is important. To improve reliability of the wireless communication cooperative techniques are introduced. In the case of cooperative schemes use virtual directivity by deploying at least a relay.

II. System Model of Aircraft

A. Network model and assumptions

In this paper, we assume that the communication network in the aircraft consists of a source node, a relay node and a destination node as Fig.1. The source node and the relay node are fixed in the aircraft cabin and the destination node is fixed to the aircraft wing. All nodes transmit data in half-duplex mode and BPSK modulation Selective Combining(SC) technique that selects only one SNR signal from a relay node and a source node are used.

B. Categorization of wireless communication in the aircraft

The performance and requirements of wireless avionics intra-communication systems are classified according to Low Inside(LI), Low Outside(LO), High Inside(HI) and High Outside(HO). In this paper, we consider both low data rate inside and outside systems. In the case of the low data rate inside system, it has the peak data rate around 1 kbit/s and average data rate around 10-800 bit/s. In the other case, it has the peak data rate around 1 kbit/s and average data rate around 10-800 bit/s.

C. Channel models and requirements in the aircraft

The channel model in an aircraft is divided into three parameters of path loss (γ_{ij}), large fading (Y) and small fading (X) and can be represented by Eq. (1). The path loss (γ_{ij}) can be obtained by using the parameter values(Group B and D) in Table I and Eq. (2) [1].

$$L = \gamma_{ij} \times Y \times X, \tag{1}$$

$$\gamma_{ij} = C_1 d^{-n} f^{-k}. \tag{2}$$

Where C is a constant offset, n and d mean exponents of distance and distance and k and f mean exponents of frequency and frequency. The large-scale fading (Y) in the intra-aircraft network has a shadowing effect of up to 4.66 dB in groups B and D. In the case of small fading(X), it is assumed that the Nakagami-m fading is applied and it experiences frequency flat fading.

TABLE I
PATH LOSS PARAMETERS IN THE AIRCRAFT

Group	Group name	k	n	C_1 [dB]
A	Intra-Flight Deck	2.45	2.00	189.8
B	Inter-Cabin	2.09	3.46	167.5
C	Inter-Cabin-to-Lower Lobe	1.86	2.49	124.5
D	Inter-Cabin-to-Exterior	1.86	2.12	118.2
E	Inter-Cabin-to-Landing Gear	1.59	1.51	77.9
F	Inter-Exterior	1.95	2.31	142.5

III. COMMUNICATION SCHEMES FOR AIRCRAFT

In order to analyze the performance of the wireless avionics intra-communication, the single-hop communication scheme, the multi-hop relay scheme and the cooperative communication schemes DF, IDF, AF, and IAF are represented. Thus, the received signal can be expressed at the destination model by Eq. (3).

$$y_{ij} = \sqrt{P_i} h_{ij} x + n_{ij}. \tag{3}$$

Where P_i is the transmitted power from the node, h_{ij} is the Nakagami-m fading channel coefficient between the nodes, x is the packet from the source or relay node, n_{ij} with a variance of $N_0/2$ is the additional white Gaussian noise(AWGN) between the nodes, where N_0 is the thermal noise power spectral density per Hz.

The outage probability between i and j channel is defined by Eq. (4).

$$\rho_{ij} = \Pr\{SNR_{ij} < \mu\} = \frac{1}{\Gamma(m+1)} \left(\frac{m\, N\, \mu}{P_i\, \gamma_{ij}} \right)^m. \tag{4}$$

Where μ is SNR threshold, in the case of single-hop scheme $\mu = 2^R - 1$, in the other cases $\mu = 2^{\theta R} - 1$, R is spectral efficiency, $\Gamma(x)$ is the incomplete gamma function, m is a Nakagami parameter, $N = N_0 B$ is the noise power spectral density in dBm/Hz, and B is the bandwidth. this is used to each schemes in common to get the outage probability of each channel.

In this paper, to meet the Q_0S(Quality of Service) requirement the minimum power from the transmitter is applied to each schemes and it can be represented by Eq. (5).

$$P_i = \frac{m\, N\, \mu (\Gamma(m+1)\, \rho_0)^{-1/m}}{\gamma_{ij}}. \tag{5}$$

Where ρ_0 means the target outage probability, which is different from a certain application.

A. Single-hop scheme

The single-hop scheme is a method of transmitting data from the source node directly to the destination node without the help of the relay node. Since the power used in the circuit board must be considered when calculating the total power used in the wireless communication of the aircraft.

The total power consumption considering the power transmitted from the source node to the destination node and the hardware power consumption can be obtained by Eq. (6) [4].

$$E_{SH} = \frac{(P_{AMP} + P_{TX} + P_{RX})\, \kappa}{R_b}. \tag{6}$$

Where R_b is bit rate, κ is the packet size, $P_{AMP} = v\, P_i$ is energy consumption of the power amplifier when transmitting, $v = {}^{\tau}/_{\omega} - 1$ is power amplifier efficiency, $\omega = \frac{P_{out}^{RF}}{P_{in}^{DC}} \times 100\%$ is the drain efficiency of the power amplifier and τ is the PAR(Peak to Average Ratio) for BPSK modulation.

P_{TX} and P_{RX} which mean the power consumptions of a transmitter and a receiver respectively can be expressed by Eq. (7), (8) [5].

$$P_{TX} = P_{BAS} + P_{MIX} + P_{SYN} + P_{FIL} + P_{DAC}, \tag{7}$$

$$\begin{aligned} P_{RX} = &P_{BAS} + P_{MIX} + P_{SYN} + P_{LNA} + P_{FIL} \\ &+ P_{IFA} + P_{ADC}. \end{aligned} \tag{8}$$

In Eq.(7) P_{BAS}, P_{MIX}, P_{SYN}, P_{FIL} and P_{DAC} mean power consumption on baseband, mixer, synthesizer, filter and digital-to-analog converter from the transmitter respectively. Further, in Eq. (8) P_{LNA}, P_{IFA}, and P_{ADC} mean power consumption on low noise amplifier, intermediate frequency amplifier and analog-to-digital converter from the receiver respectively when operating. The parameters used in the above equation, P_{TX}, P_{RX} and P_{AMP} are applied equally to multi-hop and AF, DF, IAF and IDF schemes and may have power consumption errors caused by the implementation.

In terms of throughput metric of the single-hop transmission that can be obtained by Eq. (9).

$$T_{SH} = R(1 - \rho_{SD}) \tag{9}$$

Where R is spectral efficiency, ρ_{SD} is the outage probability between the source and the destination.

B. Multi-hop scheme

The multi-hop network consists of two-hop topology. Thus, two time slots are used for the multi-hop communication, which lead to the throughput reduction to more than half compared with the single-hop communication due to delays. To complement this degradation, the bit rate of the relay node should be increased more than twice. According to the assumption that the relay node uses the same circuit as the source and the destination node, the total energy consumption on multi-hop transmission is represented by Eq. (10) [6].

$$\begin{aligned} E_{MH} = &\rho_{SR} \frac{(P_{AMP} + P_{TX} + P_{RX})\, \kappa}{\theta\, R_b} \\ &+ (1 - \rho_{SR}) \frac{(2P_{AMP} + 2P_{TX} + 2P_{RX})\, \kappa}{\theta\, R_b} \end{aligned} \tag{10}$$

Where ρ_{SR} is the outage probability between the source node and the relay node, θ is the factor to complement the throughput degradation. The first term of Eq. (10) considers the energy consumption when the relay node fails to decode the packet from source node at the relay node, and the second term considers the energy consumption when the relay node succeeds to decode and forward it to destination node.

In terms of throughput of the multi-hop transmission that can be expressed by Eq. (11).

$$T_{MH} = \frac{R}{2}\left(1-\rho_{SR}\right)\left(1-\rho_{RD}\right). \tag{11}$$

Where ρ_{RD} is the outage probability between the relay node and the destination node, the spectral efficiency is half than that of single-hop transmission due to using two time slots.

C. DF scheme

The DF communication progresses to two phases for the source node to send the packet to the destination node by cooperation with relay node. In the first phase, the source node transmits a packet to the relay node and the destination node, in the second phase the relay node transmits the packet from the source node to the destination node. Thus, the total energy consumption on three nodes in DF communication can be obtained by Eq. (12) [5].

$$\begin{aligned} E_{DF} =& \rho_{SR}\frac{\left(P_{AMP}+P_{TX}+2P_{RX}\right)\kappa}{\theta R_b} \\ &+ \left(1-\rho_{SR}\right)\frac{\left(2P_{AMP}+2P_{TX}+3P_{RX}\right)\kappa}{\theta R_b}. \end{aligned} \tag{12}$$

Where the first term means the energy consumption when the relay node fails to decode the packet from source node, and the second term means the energy consumption when the relay node succeeds to decode the packet and to carry out cooperative communication.

The DF throughput is can be expressed by Eq. (13).

$$T_{DF} = \frac{R}{2}\left(1-\rho_{SD}\right) + \frac{R}{2}\rho_{SD}\left(1-\rho_{SR}\right)\left(1-\rho_{RD}\right). \tag{13}$$

Where there are two terms, the first term means the throughput between the source node and the destination node, the second term means the throughput when communication is carried out by using relay node. The spectral efficiency of both terms is half due to the half-duplex constraint.

D. AF scheme

The AF communication is similar with the DF. However, when relay node received a signal from the source node, not to decode the signal but to amplify the signal and forward it to the destination node. This cooperative communication can be expressed by Eq. (14) [7].

$$\begin{aligned} E_{AF} =& \frac{\left(P_{AMP}+P_{TX}+2P_{RX}\right)\kappa}{\theta R_b} \\ &+ \frac{\left(P^{*}_{AMP}+P_{TX}+P_{RX}\right)\kappa}{\theta R_b}. \end{aligned} \tag{14}$$

Where $P^{*}_{AMP} = v\left(P_i - \left(P_i\gamma_{SR}+N\right)\right)$ is the transmission power from the relay node, γ_{SR} is the pathloss between the source node and the destination node. The first term represents the energy consumption when the source node transmits a packet to the source node and the destination node, and the second term is the energy consumption when the relay node conveys the packet.

In terms of throughput of the AF is the same as the DF.

E. IDF scheme

The IDF is the DF-based communication, which has three phases. In the first phase, the source node broadcasts to the relay and destination node. In the second phase, the destination node makes a decision whether to request the packet of the source node or not, and the destination node gives a ACK or NACK to the relay node and the source node. In the third phase, according to the decision of the destination node the relay node forwards the packet or keeps silent. Thus, the total energy consumption of the IDF can be expressed by Eq. (15) [6].

$$\begin{aligned} E_{IDF} =& \left(1-\rho_{SD}\right)\frac{\left(P_{AMP}+P_{TX}+2P_{RX}\right)\kappa}{\theta R_b} \\ &+ \rho_{SD}\cdot\rho_{SR}\frac{\left(P_{AMP}+P_{TX}+2P_{RX}\right)\kappa}{\theta R_b} \\ &+ \rho_{SD}\cdot\left(1-\rho_{SR}\right)\frac{\left(2P_{AMP}+2P_{TX}+3P_{RX}\right)\kappa}{\theta R_b}. \end{aligned} \tag{15}$$

Where the first term when the destination node decodes the packet sent directly from the source node, the second term when both of the relay node and the destination node fail to decode the packet from the source node, and the third term when the cooperative transmission progresses represent the energy consumption.

The IDF throughput can be obtained by Eq. (16).

$$T_{IDF} = R\left(1-\rho_{SD}\right) + \frac{R}{2}\rho_{SD}\left(1-\rho_{SR}\right)\left(1-\rho_{RD}\right). \tag{16}$$

Where the first term represents the throughput when the packet of the source is conveyed successfully to the destination node, and the second term means the throughput when the packet is conveyed via the relay node to the destination node.

F. IAF scheme

The transmission mechanism of IAF scheme is similar with the IDF, however at the relay node the message is not decoded but amplified as the AF. Thus, the total energy consumption is obtained by Eq. (17) [7].

$$\begin{aligned} E_{IAF} =& \frac{\left(P_{AMP}+P_{TX}+2P_{RX}\right)\kappa}{\theta R_b} \\ &+ \rho_{SD}\frac{\left(P^{*}_{AMP}+P_{TX}+P_{RX}\right)\kappa}{\theta R_b}. \end{aligned} \tag{17}$$

Where the total energy consumption is almost the same as the AF, the outage probability factor is added between the source node and the destination node, which means according to the packet of the source node sent directly to the destination node the total energy should be reduced.

In terms of the IAF throughput is the same as the IDF.

IV. SIMULATION RESULT

The simulation is conducted by using Matlab 2018a, and the parameters of center frequency, bandwidth, target outage probability and packet size are 4.3 GHz, 10 kbps, 10^-3 and 1024 bit respectively. Fig.1 presents the comparison with six schemes by the total energy consumption as spectral efficiency.

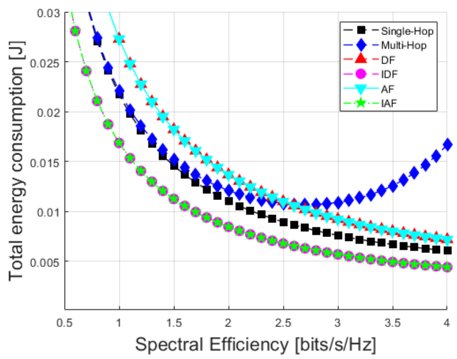

Fig. 1. Total energy consumption vs. Spectral Efficiency

In Fig.1 according to the overall trend of the spectral efficiency at $SNR_{SD} = 0dB$ the IDF, IAF cooperative schemes perform better than the others because those can reduce transmission energy by using incremental function that decides to use the relay node by ACK from the source node. The difference of total energy consumption among the incremental cooperative scheme and others is very low due to low bandwidth and small distance interval between nodes.

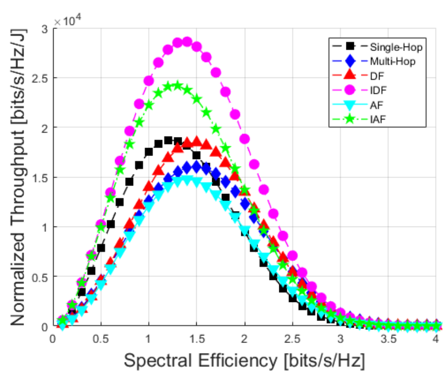

Fig. 2. Normalized Troughput vs. Spectral Efficiency

Fig.2 represents Normalized Throughput according to spectral efficiency at $SNR_{SD} = 0dB$. the IDF scheme outperforms the others in overall spectral efficiency due to low communication failure compared with the others. When the DF, AF performance are compared, the DF scheme is better in overall spectral efficiency. Thus, decoding mechanism can save the energy more than amplifying mechanism. In Fig.3 normalized throughput is shown corresponding to SNR_{SD}. In low SNR the IDF performance is the best, and the IAF performance is similar with the IDF. When SNR increases

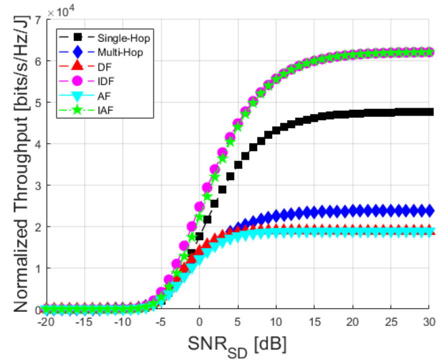

Fig. 3. Normalized Troughput vs. SNR

single-hop scheme has higher performance than multi-hop, DF, AF schemes because the signal power is strong enough to send packet successfully, which means that it can save the usage of time slots.

V. CONCLUSION

In this paper, the channel of the aircraft is modeled by referring ITU-R M.2283, and the performance of the total energy consumption and throughput is represented in the channel model of the aircraft. The total energy consumption including hardware energy consumption is considered and demonstrated. As a result of performance, the IDF and IAF schemes perform better than the other schemes in the total energy consumption, In terms of normalized throughput, the IDF scheme outperform the others.

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