A New Simple Unmanned Aerial Vehicle Doppler Effect RF Reducing Technique

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***Abstract*—The purpose of this paper is to present a solution to reduce the Doppler effect in wireless communication systems. As distance increases, pathloss increases too and the signal to noise ratio decreases. A major problem that affects the quality of the link is the horizon. A solution to improve signal quality is to use an Unmanned Aerial Vehicle (UAV) relaying far mobile stations to the base station. However, because of UAV's speed, Doppler frequency shift decreases the signal to noise ratio and cannot be supported by the base station for the values that are higher than the measured limit. The simple solution explained in this paper reduces dramatically the Doppler effect and makes possible the use of UAVs, as a repeater, to extend the communication even at high speed.**

Keywords— RF, Doppler, compensation technique, UAV.

I. INTRODUCTION

Today's ship-to-ship or ship-to-shore is limited by the horizon. The received signal power depends highly on the altitude of the transmitters [1]. Moreover, over the last few years, interest in wireless communications by using unmanned aerial vehicle located at low altitude comparing to satellites has increased [2, 3]. The use of UAVs is an increasing research area for military operations and communications [2].

The UAV is a low cost communication infrastructure that can provide a high quality communication link between wireless terminals [4]. The UAV is equipped with a transponder that relays different terminals. One of the important advantages is the reliable and high performance wireless communication links among UAV. However, the wireless communication channel in UAV case is different to the traditional wireless land channel. In traditional wireless land communications, the base station is fixed and the mobile station has a typical relative speed of less than 120 km/h. However, the speed of the UAV can reach 800km/h. In fact, the high speed of UAV leads to a large Doppler spread. As a result, the communication quality degrades according to in laboratory test and characterization. For example, in the case of an OFDM waveform system, the orthogonality between subcarriers degrades leading to high amount of interference between them [5]. Therefore, the signal to noise ratio decreases and the bit error increases. This Doppler shift should be compensated to prevent inter subcarriers interference.

In the literature, various Doppler compensation techniques have been proposed. The traditional method of using guard bands to combat Doppler will result in big waste of system bandwidth [6, 7]. Most of the compensation techniques are implemented in the terminal's processor which needs the demodulation of the RF signal before its retransmission in the case of the use of relay station [8, 9]. An FFT based technique to estimate the Doppler offset on a CW pilot carrier present on the LEO downlink channel was used by [10]. However the performance of this technique is affected by the multipath [11]. Another idea used in high-mobility OFDM uplink transmission is presented by [12]. It is based on the analysis of the difference between the uplink and the downlink transmission. Unfortunately, it requires the separation of different multi-paths in spatial domain [12]. An equalization technique was proposed by [5] to compensate Doppler effect. This complex technique supposes a constant Doppler shift within an OFDM block and perfect channel knowledge. In addition to digital techniques, an analog Doppler compensation technique involving the carrier tracking loop and the compressive receiver technique was proposed by [13]. The main drawback of the analog technique is the implementation difficulties. Another technique is based on Doppler measurement and then pre-compensation [7].

This paper presents a new simple and promising technique to compensate the frequency Doppler shift. It is a pure RF technique and the demodulation of the signal is not needed at the UAV. In this paper, it is demonstrated that a judicious choice of direct conversion architecture, especially the choose of mixing type and the value of phase-locked loop frequency can compensate the Doppler effect caused essentially by the UAV's motion.

The remainder of this paper is organized as follows: The first section gives an overview about the Doppler phenomena and presents measured performance of a wireless communication system behind a pure Doppler shift. The second section gives details about the proposed technique. Then in the third section simulation results are presented. In the last section, an overview of the proposed UAV transponder architecture is presented.

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I. Wireless Communication System Doppler Performance Characterization

For a moving receiver, the main frequency of the carrier f_0 will drift with $\pm\Delta f$, depending on the direction of the motion of the receiver [14]. Let f_c be the transmitter carrier frequency, v(t) be the relative speed between the transmitter and the receiver, and α(t) be the angle between the relative velocity and the signal propagation direction [7]. Then, the received carrier frequency is:

$$f = f_c + \frac{f_c v(t)\cos(\alpha(t))}{c}. \quad (1)$$

where c is the light celerity. The aim of this paragraph is to present the limitation of a base station, already existing in the market, in terms of mobile stations velocities. Since the air testing is unrepeatable and susceptible to a very large number of uncontrollable distortions, the channel simulator, Propsim C8, that simulates virtually a wireless channel is used. Instead of transmitting over the air, the signal is transmitted through a channel simulator that provides highly reliable and repeatable testing.

The test setup consists of a base station connected to a mobile station through the channel simulator. Fig. 1 illustrates the laboratory setup. Isolators are used to control independently the uplink and downlink traffics. Variable RF attenuators are used to adjust input power levels of different equipment.

Fig. 1. In laboratory Doppler effect characterization.

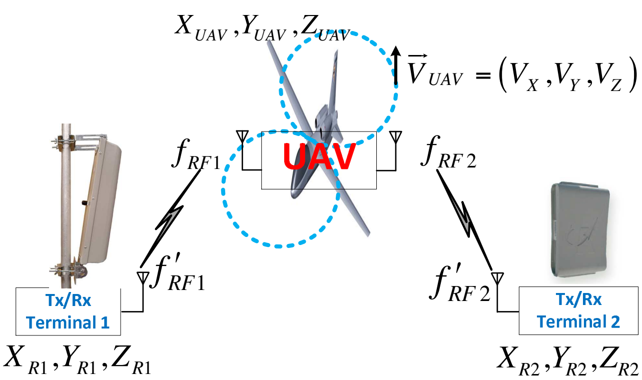


Fig. 2 An UAV having 8 shape trajectory relaying a BS to a MS

Doppler Test of the system with a direct path including a pure Doppler shift, shows that the maximum possible carrier Doppler shift is 956.22 Hz which corresponds to a mobile station speed of 208 km/h operating at 4.965GHz for example

II. RF Doppler Shift Reducing Technique

A Doppler shift occurs when a mobile station moves and causes a frequency shift. The frequency increases when the MS rolls away the BS and decreases when the MS approaches to the BS. In an OFDMA system, a pure Doppler shift causes a shift of subcarriers in the same manner.

To circumvent this limitation in a case of an UAV relaying two terminals (see Fig. 2), a solution is to use a repeater which does not demodulate the signal at the UAV but just re-transmits it to the ground after a small frequency shift. The choice of Phase Locked Loop (PLL) frequency and the RF I/Q modulation mode is important for Doppler effect minimization. Indeed, at the output of a mixer excited by oscillator frequency and an RF signal, we get the following positive frequency components $f_{RF2}= f_{LO}+f_{RF1}$ and $f_{RF2}= f_{LO}-f_{RF1}$ if $f_{LO} \geq f_{RF1}$ or $f_{RF2} = f_{RF1}- f_{LO}$ if $f_{RF1} \geq f_{LO}$.

In the first case, where $f_{RF2}= f_{LO}+f_{RF1}$, it is assumed that the two terminals have negligible velocities comparing to that of the UAV. The first terminal sends a signal with a frequency f'_{RF1}. Because of the Doppler effect, the UAV receives f_{RF1} given by:

$$f_{RF1} = f'_{RF1} + \frac{f'_{RF1}}{c} V_{UAV-R1}. \quad (2)$$

where

$$V_{UAV-R1} = \frac{(X_{UAV}-X_{R1})V_X + (Y_{UAV}-Y_{R1})V_Y + (Z_{UAV}-Z_{R1})V_Z}{\sqrt{(X_{UAV}-X_{R1})^2 + (Y_{UAV}-Y_{R1})^2 + (Z_{UAV}-Z_{R1})^2}} \quad (3)$$

The coordinates $(X_{UAV},Y_{UAV},Z_{UAV})$ and (X_{R1},Y_{R1},Z_{R1}) are respectively of the UAV and the first terminal. The set (V_X, V_Y,V_Z) are the coordinates of UAV's speed vector. The received frequency is converted to $f_{RF2}= f_{LO}+f_{RF1}$. In the other direction from the UAV to terminal2, the frequency of the signal received by the terminal2 is f'_{RF2} expressed in:

$$f'_{RF2} = f_{RF2} + \frac{f_{RF2}}{c} V_{R2-UAV} \quad (4)$$

where

$$V_{R2-UAV} = \frac{(X_{R2}-X_{UAV})V_X + (Y_{R2}-Y_{UAV})V_Y + (Z_{R2}-Z_{UAV})V_Z}{\sqrt{(X_{R2}-X_{UAV})^2 + (Y_{R2}-Y_{UAV})^2 + (Y_{R2}-Y_{UAV})^2}} \quad (5)$$

The coordinates (X_{R2},Y_{R2},Z_{R2}) are of the second terminal. Thus, the total Doppler frequency shifts is in:

$$f'_{RF2} - (f_{Lo} + f'_{RF1}) = \left\{ f_{Lo} + f'_{RF1}\left(1+\frac{1}{c}V_{UAV-R1}\right)\right\} \\ .\left\{1+\frac{1}{c}V_{R2-UAV}\right\} - f_{Lo} - f'_{RF1} \tag{6}$$

In the other direction, the expression of the frequency f_{RF2} of the signal received by the UAV and emanated from terminal2 is given by:

$$f_{RF2} = f'_{RF2} - \frac{f'_{RF2}}{c}V_{R2-UAV} \tag{7}$$

The frequency f'_{RF1} of the signal received by terminal1 and emanated from the UAV is:

$$f'_{RF1} = \left\{-f_{Lo} + f'_{RF2}\left\{1-\frac{1}{c}V_{R2-UAV}\right\}\right\}\left\{1+\frac{1}{c}V_{R1-UAV}\right\}. \tag{8}$$

The second case where $f_{RF2}= f_{RF1}-f_{LO}$ if $f_{RF1}\geq f_{LO}$ is equivalent to the first case where $f_{RF1}= f_{LO}+f_{RF2}$. In the third case where $f_{RF2}= f_{LO} - f_{RF1}$ if $f_{LO}\geq f_{RF1}$, the expression of f'_{RF2} in terms of f'_{RF1} is in:

$$f'_{RF2} = \left\{f_{Lo} - f'_{RF1}\left(1+\frac{1}{c}V_{UAV-R1}\right)\right\}\left\{1+\frac{1}{c}V_{R2-UAV}\right\}. \tag{9}$$

The expression of the total Doppler is expressed in:

$$f'_{RF2} - (f_{Lo} - f'_{RF1}) = \left\{f_{Lo} - f'_{RF1}\left(1+\frac{1}{c}V_{UAV-R1}\right)\right\} \\ .\left\{1+\frac{1}{c}V_{R2-UAV}\right\} - f_{Lo} + f'_{RF1}. \tag{10}$$

In the other direction, the expression of f'_{RF1} in terms of f'_{RF2} is in:

$$f'_{RF1} = \left\{f_{Lo} - f'_{RF2}\left\{1-\frac{1}{c}V_{R2-UAV}\right\}\right\}\left\{1-\frac{1}{c}V_{UAV-R1}\right\}. \tag{11}$$

In the fourth case, where there is no frequency conversion at the UAV i.e $f_{RF1} = f_{RF2}$, the frequency of the signal received by the terminal2 is expressed in:

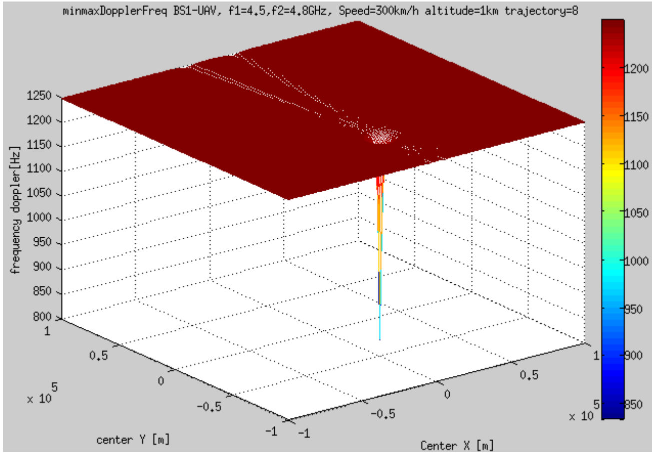
$$f'_{RF2} = f'_{RF1}\left\{1+\frac{1}{c}V_{UAV-R1}\right\}\left\{1+\frac{1}{c}V_{R2-UAV}\right\}. \tag{12}$$

The total Dopper frequency offset $f'_{RF2} - f'_{RF1}$ is calculated in:

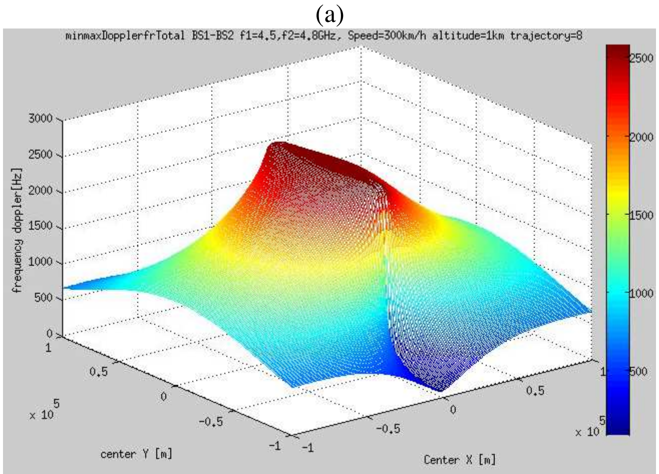
$$f'_{RF2} - f'_{RF1} = f'_{RF1}\left\{\left\{1+\frac{1}{c}V_{UAV-R1}\right\}\left\{1+\frac{1}{c}V_{R2-UAV}\right\}-1\right\}. \tag{13}$$

III. COMPARISON BETWEEN DIFFERENT CASES

The UAV is used as an airborne repeater to provide area extension. A Matlab simulation is done for an UAV relaying two terminals at both sides. It has an 8 shape trajectory for fuel consumption and usury purposes. The radius of each mi-8 trajectory is 1.2 km. The speed is 300 km/h. the center of trajectory is 15 km far to each terminal. The following figure illustrates the behavior of Doppler shift for this case.



(a)



(b)

Fig. 3 Maximal Doppler Frequency between a terminal (mobile station) and the UAV as a function of X-axis and Y-axis trajectory translation (a). Maximal Doppler Frequency between two terminals through an airbone repeater as a function of X-axis and Y-axis trajectory translation (b).

In the first case and for f'_{RF1}=4665MHz, f_{LO}=300MHz and f'_{RF2}=4965MHz. The altitude of UAV is 1 km. The result of the simulation is illustrated in Fig. 3. The maximum Doppler shift between the two terminals is 3566 Hz. The maximum Doppler shift between the UAV and a terminal is 1727.4 Hz. This concept cannot be retained since maximal Doppler shift is greater than 956.22 Hz. The second case is equivalent to the first case. Thus, maximum Doppler frequency shift is the same as in the first case.

In the third case, the operation frequency of terminal1 is f'_{RF1}=4665MHz and of terminal2 f'_{RF2}=4965MHz. The frequency of the local oscillator in UAV's transponder f_{Lo}=9630 MHz. The result of the simulation is illustrated in Fig. 4. The maximum Doppler shift between the two terminals is 182.17 Hz. The maximum Doppler shift between the UAV and a terminal is 1727.4 Hz. The Doppler effects is minimized

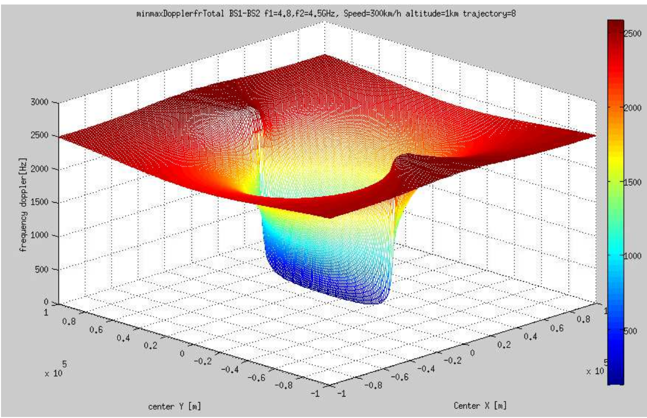
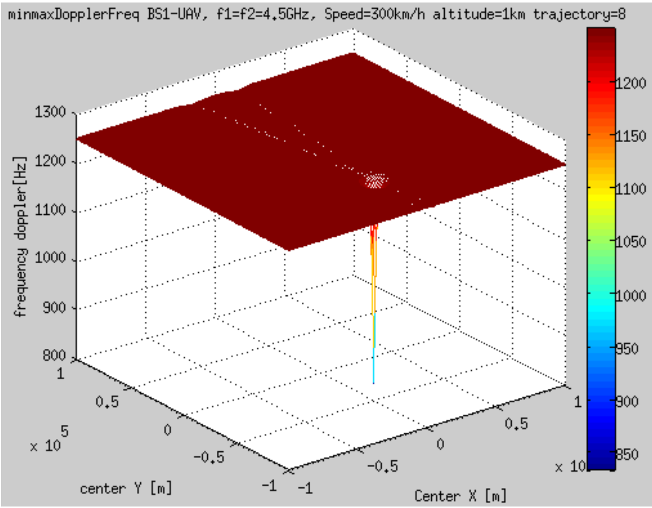
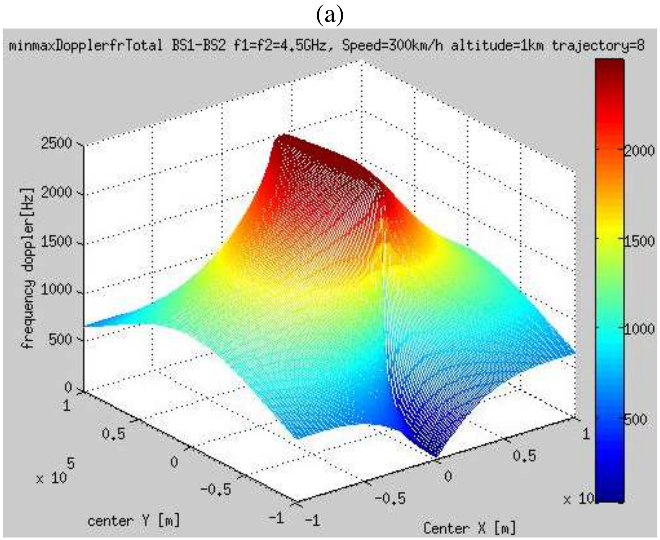


Fig. 4 Third case maximal Doppler frequency between two terminals through an airbone repeater as a function of X-axis and Y-axis trajectory translation



(a)



(b)

Fig. 5 Maximal Doppler Frequency between a terminal and the UAV as a function of X-axis and Y-axis trajectory translation (a). Maximal Doppler Frequency between two terminals through an airbone repeater as a function of X-axis and Y-axis trajectory translation (b).

dramatically. This concept is retained since maximal Doppler shift is lower than 956.22 Hz in an acceptable area. In the fourth case, where there is no frequency conversion is applied at the UAV. It means that the UAV will receive and retransmit the same signal at the same frequency. The result of the simulation is presented in Fig. 5 where the frequency of operation is 4.5 GHz. According to the obtained results, this solution cannot be retained since it reduces the Doppler effects in the outer zone.

IV. Overview of the UAV transponder architecture

In the first or second cases, the Doppler effect is reduced in the outer region between the two terminals as shown in Fig. 3. However, in the third case, the Doppler effect is reduced in the inner region where the UAV is supposed to relay between the two terminals. As the communication link is bidirectional, the transponder includes two RF repeaters. The received signal is amplified by a low noise amplifier, then filtered by an image rejection filter. The Phase look loop generates a stable frequency which is the sum of f_{RF1} and f_{RF2}. After the mixer, the signal centered at f_{RF2} is filtered then amplified by a high power amplifier. The architecture of the transceiver is illustrated in Fig. 6.

It is possible to build adaptive Doppler compensation technique by switching between the second and third cases. The choice of PLL's frequency depends on the geographic positions of the relay station and of the terminals. If the UAV is in the inner zone, the PLL generates $f_{Lo}= f'_{RF1}+f'_{RF2}$ and switches to $f_{Lo}=abs(f'_{RF1}-f'_{RF2})$ when the UAV moves to the outer zone. The result of the simulation of this case is illustrated in Fig. 7. From the figure, it is observed that the surface of the region where the total acceptable Doppler frequency between the two terminals increases. To determine the position of the UAV, complex digital signal processing algorithms should be implemented in the UAV. Thus, the adaptive solution consists on switching between third technique and the first or second technique by using a multi-band PLL, a programmable RF IQ modulator and a baseband part to add intelligence to UAV for the calculation of UAV's position.

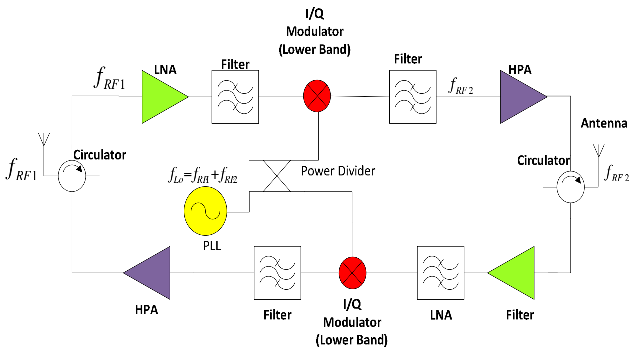


Fig. 6 UAV transponder architecture.

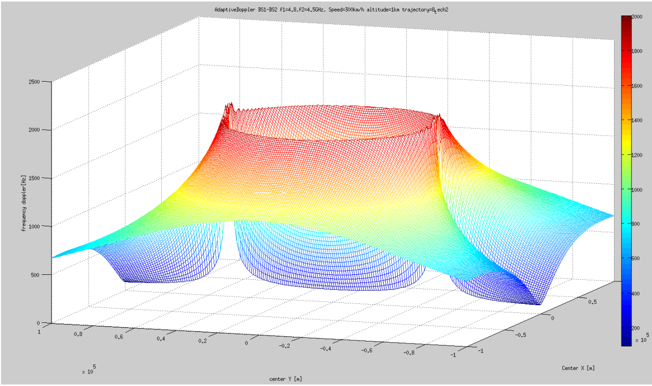


Fig. 7 Adaptive case maximal Doppler frequency between two terminals through an airbone repeater as a function of X-axis and Y-axis trajectory translation

V. Conclusion

In this paper, a technique to compensate the Doppler effect generated by an UAV relaying two terminals is presented. The use of an UAV has the advantage of improving the quality communication link between wireless terminals, especially, to circumvent the horizon limitation in maritime, air-to-air or, even, land communications. However, the major problem of using an UAV to relay between two terminals is its speed. Indeed, the motion of the UAV generates a Doppler effect that drifts the carrier frequency of the signal. The frequency offset affects the communication quality especially for those based on OFDM. An in-lab characterization of a traditional terrestrial radio demonstrated its inability to be used in a wireless link involving UAV which is due principally to its high speed. The compensation technique demonstrated and validated in this paper reduces dramatically the Doppler effect caused by the UAV. The technique is a simple, low cost and energy efficient solution. The analog-digital signal conversion is not needed which allows to keep only the RF part of the conventional radio architectures and a judicious choice of PLL's is the basic point to resolve the problem. Moreover, an overview of the transceiver architecture is presented. The details will be presented in a future works. The solution is satisfactory and keeps end-to-end Doppler shift within the limits required to maintain a reliable end-to-end communication link. An investigation on adaptive Doppler compensation technique will be a plus. Coherence time of the channel will be analyzed in the future especially when high speed aerial platforms are used.

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