Measurement and Analysis of Radiation Leakage From a GPS Module for the Detection of Drones

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***Abstract*—Radiation leakage of a global positioning system (GPS) module was investigated for a drone detection system by measuring the attenuation effect and long-range detection on the outside of a building. The GPS module consisting of the radio frequency components is essential to control the flight of a drone. There is an unavoidable leakage in the GPS module during operation, and the leakage signal from the GPS module was analyzed and detected with a high-sensitivity receiver. To analyze the leakage from the GPS module during operation, we obtained the whole frequencies of leakage signals and the radiation pattern of a drone with the GPS module in an anechoic chamber. From the data, we measured the leakage signals in an outdoor space. Through outdoor measurement, it was confirmed that the theoretical attenuation effect was consistent with the measured value with a distance variation. Finally, the GPS leakage in the drone was measured up to 950 m with a high signal-to-noise ratio (SNR) of 25 dB.**

***Index Terms*—Drone detection system, high-sensitivity receiver, outdoor experiment, radiation leakage signal from global positioning system (GPS).**

I. Introduction

FOR several years, the small drone industry has soared in popularity as both a promising industry and a thrilling hobby. As the drone industry grows, the need for an air-traffic collision avoidance system and terror prevention on presidential residences and nuclear power plants is increasing [1], [2]. Conventional radar systems can hardly detect small drones because they have small radar cross sections (RCSs). Moreover, a classification technique to distinguish between small drones and birds is required because the RCSs of drones are similar to those of birds [3], [4].

Frequency-modulated continuous-wave (FMCW) and pulse are types of radar techniques that have been widely deployed for target detection. Such conventional radar systems use transmitter and receiver parts and capture echo signals to detect drones. For FMCW radar systems, there are technical considerations, such as the improvement of phase noise and linearity in a frequency ramp, synchronization between transmit and receive sites, and leakage problems [5], [6]. For pulse radar systems, there is a need for a power amplifier that emits a high RF power for a short time supporting the appropriate frequency band. Such power amplifiers are usually costly, which increases the price of a whole radar system. High power consumption incurs high maintenance cost as well.

The RF circuitry inside the global positioning system (GPS) module generates an inevitable small leakage. An RF module produces two types of leakage signals. The first type is generated by an RF module on its own circuit, such as line-to-line leakage, or *Tx*-to-*Rx* leakage. Studies have been conducted to reduce such leakage [7], [8]. The second type of leakage is radiation leakage, in which interference signals generated by the local oscillator (LO), amplifier, and mixer of the receiver are radiated. The radiation leakages can affect other devices outdoors [9]. However, inversely, if the leakage emitted is measured, the direction of the RF module can be estimated. To precisely control a drone, a GPS receiver module needs to be essentially included so that the drone pilot recognizes the drone's position when the drone is no longer visible. GPS leakage detection can detect drones except for birds.

This letter proposes a novel drone detection system that senses leakage from a GPS module instead of the conventional FMCW or pulse radars. The GPS leakage detection system can detect small drones without any *Tx* parts and can distinguish drones from birds, which have similar RCSs. The proposed system can be realized in a simple structure with a relatively low cost compared with the conventional radar systems using transceivers. It has an additional advantage that the system is eco-friendly because it consumes less power. Moreover, a clutter removal algorithm is not required, which makes the software simpler because it does not require a *Tx* part.

II. GPS Receiver Module Analysis

To detect the radiation leakage generated by the GPS module, we analyzed which frequency band is the most advantageous for detection. Through circuit analysis and measurement, the power of leakage is analyzed and the leakage radiation pattern of the GPS module mounted on a drone is measured to choose the frequency band.

A. Frequency Analysis of the GPS Module

Here, we used a commercial GPS module, YGG-U3535A, to detect the leakage from it. The leakage frequency of the GPS module was analyzed based on the datasheet of the GPS module,

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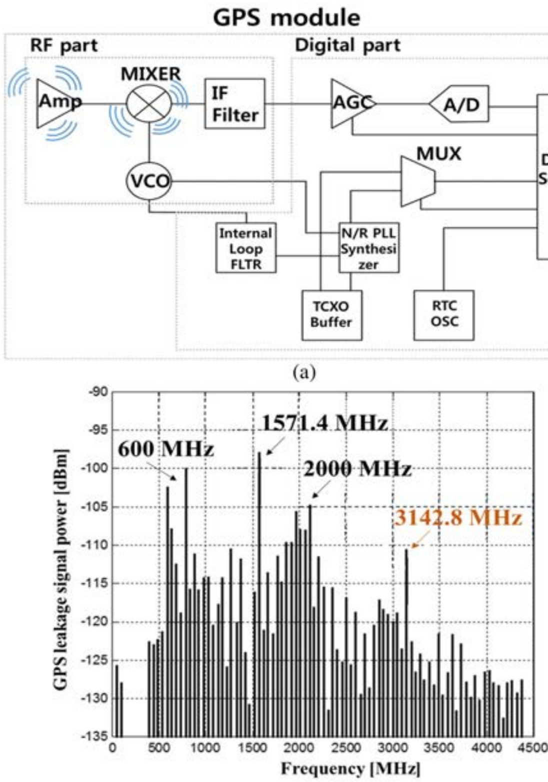

Fig. 1. (a) Block diagram of the commercial GPS module composed of RF and digital parts. From the RF part, radiation leakage is generated mainly with amplifier, mixer, and voltage control oscillator (VCO). (b) Measured result of leakage originated from the GPS module in the anechoic chamber. Several peaks were observed at 600, 1571, 2000, and 3142 MHz.

which provides a block diagram and information about the clock oscillator. Fig. 1(a) depicts a simplified block diagram of the GPS module, including an RF part and signal processing circuitry. The leakage of the GPS module can be assumed to be generated from the inside the RF part. In particular, an amplifier and a mixer mounted in the first part of the RF circuit are typical nonlinear components. Therefore, leakage with diverse frequency bands is generated.

Because a reference signal of 16.369 MHz was used to generate the LO in the GPS module, we measured the frequency of multiples of 16.369 MHz. A spectrum analyzer with a setting of both 100 Hz video resolution and bandwidth resolution and a horn antenna was utilized for the measurement. The leakage measured from the GPS module is shown in Fig. 1(b). It showed a low power level because the spectrum analyzer was used without any amplifiers. The maximum power was obtained at 1571.4 MHz, which was used in the LO for the mixer. Additionally, relatively high power leakage was observed around the 600 and 2000 MHz bands, and 3142.8 MHz, which is a harmonic of 1571.4 MHz. The 600 MHz band is not appropriate since the antenna size would be too large. In addition, the higher the frequency, the higher the directivity. High directivity makes longer distance detection feasible. Therefore, the 2000 MHz band or 3142.8 MHz has an advantage for drone detection. Here, we chose the 3142.8 MHz band, which is the second harmonic of the LO because the 2000 MHz band has a relatively high-noise floor. Although this result was obtained from a commercial GPS module, it is also applicable to other GPS modules in drones that do not provide information about the inner structure, because every GPS satellite transmits the $L1$ frequency centered at 1575.42 MHz.

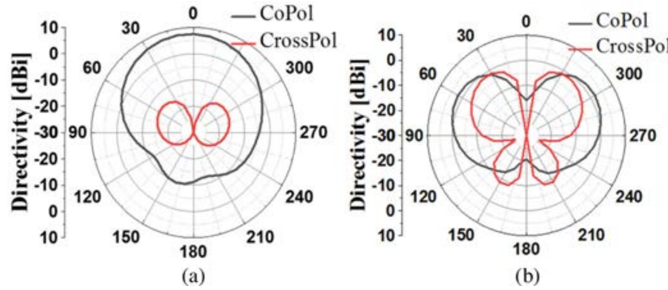

Fig. 2. Simulated radiation patterns of a typical microstrip patch antenna (a) at 1.57 GHz and (b) at 3.15 GHz.

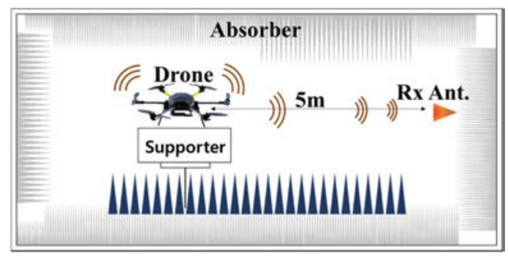

Fig. 3. Measurement setup of the GPS module of the drone in the anechoic chamber.

B. Radiation Direction of the GPS Leakage

The direction of radiation is measured for selecting the frequency for detection. Fig. 2 shows the simulated radiation patterns of a rectangular patch antenna commonly used in GPS modules.

In 1.57 GHz, the radiation pattern of a typical patch antenna is shown. However, in 3.15 GHz, which is a harmonic frequency, it was found that more radiation was generated from both sides and below. The detection angle of the drone is mainly from side directions (90°–120°, 240°–270°). Therefore, this side gain is higher in the 3.15 GHz band.

Radiation leakage of a GPS module mounted on drones, a hexacopter, and an Inspire 1 from Dà-Jiāng Innovations (DJI), was measured in an anechoic chamber, as shown in Fig 3. The peak gain of the *Rx* antenna used in the anechoic chamber is 16 dBi. Fig. 4 shows the result of measuring the leakage power according to the angle of the drones. An amplifier of 14 dB was used for the leakage of 1.57 GHz, and the leakage of 3.15 GHz was measured using an LNB of 60 dB gain. As seen in Fig. 4(a) and (b), the emission was concentrated in the upward direction in the 1.5724 GHz band for the hexacopter. Only the hexacopter

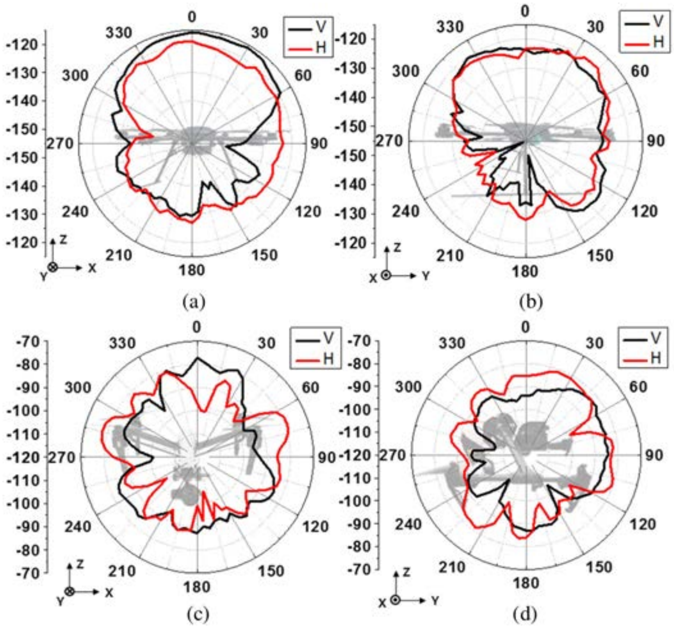

Fig. 4. Radiation leakage power measured in an anechoic chamber. (a) *zx* plane at 1.5724 GHz. (b) *yz* plane at 1.5724 GHz. (c) *zx* plane at 3.1444 GHz for hexacopter. (d) *zx* plane at 3.1444 GHz for Inspire 1.

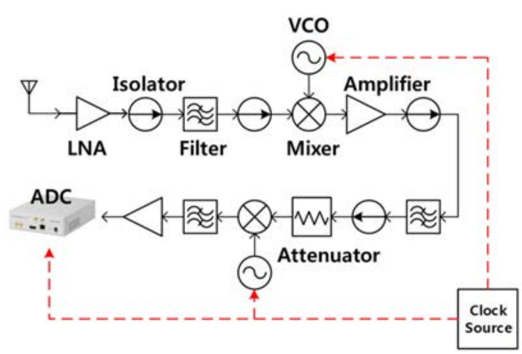

Fig. 5. Overall system block diagram of the GPS leakage receiving system composed of an LNA, isolator, filter, mixer, VCO, and attenuator. An ADC was used to monitor the signals.

was measured at 1.5724 GHz signal because the 1.5724 GHz signal for Inspire1 was too low to be measured. On the other hand, as seen in Fig. 4(c) and (d), it was confirmed that more radiation occurred sideways in the 3.1444 GHz band.

III. Experimental Verification

A. High-Sensitivity Receiver for GPS Leakage

The proposed system adopts a double superheterodyne that has high sensitivity and frequency selectivity as shown in Fig. 5. The signal received from the antenna goes through a low-noise amplifier (LNA) with a gain of 60 dB. The first LO frequency is 5954 MHz, and the second LO is 2880 MHz. The image signal is completely suppressed with the first LO frequency. Finally, a 70 MHz intermediate frequency (IF) signal is applied to a USRP n210 that functions as an analog-to-digital converter (ADC) and has a maximum sampling rate of 100 MHz.

The signal to be received is in the 3.144 GHz band. Since the first LO frequency is 5954 MHz, a high-side LO (HSLO) is used. With the HSLO, the IF is almost unaffected by the harmonics of the LO and RF. This considerably increases the dynamic range of the system [10]. The frequency was determined by considering image rejection. If the radio wave is not used in the IF + LO frequency band, there is no image signal to be received from the receiving system. Thus, the burden of image rejection is reduced. The first LO frequency was determined to be 5954 MHz with an IF of 2810 MHz. Because the image frequency is LO + IF, 8764 MHz can be considered in line with the Doppler navigation frequency band, which is rarely used, thus reducing the consideration of the image frequency. LO2 was selected as 2880 MHz and downconverted to 70 MHz, a commonly used and compatible IF. The harmonics were easily removed because they were set to HSLO. A sharp filter and isolator were inserted in the middle to suppress the howling effect, harmonic rejection, and interference signal suppression.

The performance of the main components of the system, the LNA, mixer, and amplifier, was assessed. The performance of the most important part of the receiving system, the LNA, was measured by Agilent's N8975A and a noise source, N4000A. The result was obtained with a gain of 60 dB and a noise figure (NF) of 1.67 dB. An IF amplifier was added to compensate for the mixer's conversion loss. Although the NF of each component is high, the high gain and low NF of the LNA keep it low until the end of the system. The total NF can be calculated by

$$F = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} \cdots \frac{F_N - 1}{G_1 G_2 \cdots G_{N-1}} \quad (1)$$

where Fn is the noise factor of stage *n* and Gn is the gain of stage *n*. The total NF was 1.6702 dB, and the final gain was 82.2 dB, completing the system with high sensitivity. The LNA's P1dB input was -54 dBm, and the P1dB input at the system end was 85 dBm.

B. Outdoor Experiment for Verification

The radiation pattern was measured in the chamber, and the measurement system was designed and fabricated. Still, there was a need to carry out an outdoor experiment to confirm the GPS power attenuation effect and long-distance measurement for radar applications. The outdoor experiment was conducted with the settings on the roof-top of Jin-Ri Hall on the KAIST Mun-Ji campus in South Korea, as shown in Fig. 6.

The fabricated receiver system was used in the outdoor experiment. The reflector antenna has a peak gain of 35.4 dBi, 3 dB beamwidth of 2.2°, and sidelobe level of 18 dB when simulated at 3.14 GHz.

The radar equation used in the general radar shown in (2) is inversely proportional to the fourth power of *R*. However, because the GPS receiver receives the radio waves generated by

Fig. 6. Experimental setup for the GPS leakage detection in the outdoor environment.

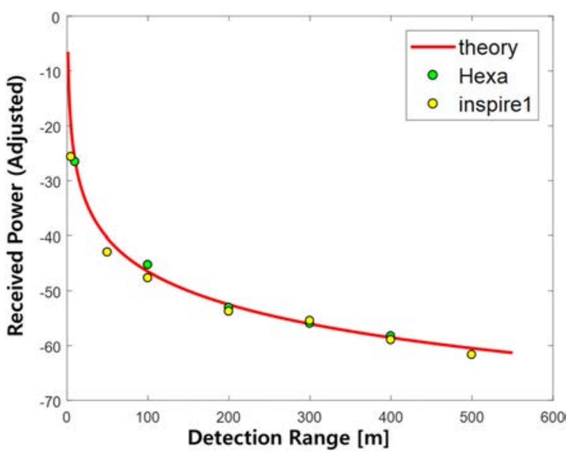

Fig. 7. Measured attenuation curve with respect to distance and two drones.

the drone, power is reduced in inverse proportion to the square of *R* with the Friis free space equation, as shown in (3). In other words, the GPS receiver is advantageous for power loss over distance

$$P_{Rx\_\text{radar}} = \frac{P_t G_t G_r \lambda^2 \sigma}{(4\pi)^3 R^4} \quad (2)$$

$$P_{Rx\_\text{GPS\_leakage}} = \frac{P_t G_t G_r \lambda^2}{(4\pi R)^2} \quad (3)$$

where P_t is the transmitted power at the transmitter output, G_t is the transmit antenna gain, G_r is the receiver antenna gain, λ is the wavelength of radar operating frequency, σ is the radar cross section in square meters, and *R* is the distance between the system and a drone.

The GPS leakage was measured according to the distance between a drone and antenna in the vertical direction. The result is shown in Fig. 7 after power calibration. It was confirmed that the ideal graph and the measured value are inversely proportional to the square of distance with similar patterns.

Fig. 8 shows the measurement results of drone flying horizontally near the ground with unwanted ground clutter. The GPS leakage was measured in terms of the distance of the drone. The elevation angle of the antenna is about 18° and the farthest measurements were made at a horizontal distance of 900 m and a height of 300 m, so the total distance is 950 m. It is

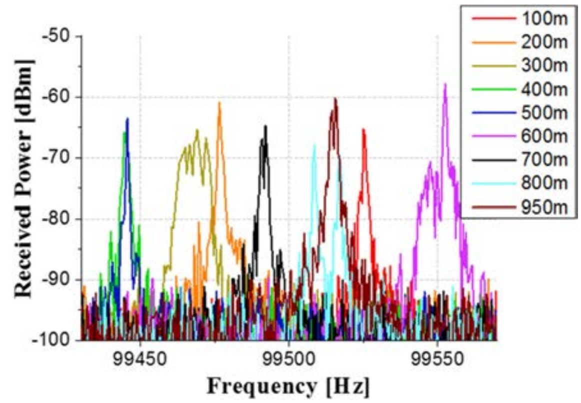

Fig. 8. FFT results according to the distance of the horizontally flying drone.

indeed possible for the drone to fly farther. However, it could be more difficult to maintain the alignment due to the narrow beamwidth. In this experiment, it was verified that the receiver system could sense the GPS leakage from about 1 km away. After downconversion to 69.9 MHz to avoid dc offset using the USRP n210, the data were acquired with a 300 kHz sampling rate using USRP n210.

In horizontal flight, the signal power was about −50 dBm and the signal-to-noise ratio (SNR) was over 25 dB. The frequency spread of the data in the figure was seen in some cases because the Doppler phenomenon occurred due to the unfixed position of the drone. Wind or control error can make the drone wobble. This is the reason for the frequency discrepancy of about 100 Hz between the peaks seen in Fig. 8. Therefore, we can assume the Doppler frequency for each side is 50 Hz. The Doppler frequency of 50 Hz means 2.38 m/s, with a carrier frequency of 3144 MHz. This is a reasonable result since the maximum velocity of the drone is 5 m/s. Because the beamwidth is narrow, it is difficult for a drone to locate in the antenna beamwidth completely. When moving the drone, the angle of the drone changed and the radiation gain was different, so the accurate gain was not measured in the horizontal measurement.

IV. CONCLUSION

Radiation leakage of a GPS module for drone detection was measured and analyzed theoretically and experimentally. We made a high-sensitivity receiver to receive the weak power of radiation leakage from the GPS module. We measured the radiation pattern of leakage power in an anechoic chamber and outdoor field measurements for analysis. We confirmed that the outdoor measurement results were in good agreement with the theoretical Friis free space equation. As a result of using a high-gain antenna, the SNR of the signal received from the drone GPS module at 950 m was about 25 dB. Based on this result, it is possible to detect a drone and estimate its direction with the received GPS leakage signal.

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