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Evaluation of skew-planar antenna for UAV communication at 2.4 GHz band

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Abstract. Skew-planar antenna is suitable for unmanned aerial vehicles (UAVs) since it has circular polarization (avoiding polarization-mismatched), omnidirectional radiation pattern (low pointing loss) thus comply with maneuver angles of UAV, and also small size. Investigation with electromagnetic simulations shows that tilt angle and coaxial length are the most sensitive parameters. Modified design with 55º tilt angle (original design: 45º) and 100 mm coaxial length (original: 60 mm) potentially provides wider bandwidth (400 MHz vs. 290 MHz), better impedance-matched ($|S_{11}|$: -47.1 dB vs. -13.6 dB), and better gain (1.98 dBi vs 1.61 dBi). The antenna is predicted capable to support service distance of 3 km in 2.4 GHz band if used with communication module with 18 dBm transmit power and -100 dBm receiver sensitivity. Therefore, the modified antenna is suitable to be applied in UAV.

1. Introduction
Communication system is one of the most important systems on an unmanned aerial vehicle (UAV). The performance of this system determines the maximum flight range and the adaptability in complex environment [1]. UAVs have several challenges to keep reliable communication through long distance, wide area, and flight maneuver and height angles, in all flight condition. UAVs fly on route by adjusting their pitch, yaw, and roll angles during their missions. It means that relative angle between UAVs and their ground station controllers (GSCs) are changing during the mission. If both UAVs and GSCs communicate to each other using linearly-polarized antennas, the UAVs' maneuvers are expected to produce polarization-mismatched. This effect reduce signal power captured by receive antenna and may result in communication interruption that in some situation are fatal for a mission. To avoid this problem, circularly-polarized antennas are installed at UAVs and GSCs. The wide angle maneuvers, variability of height and distance also suggest the use antennas with wide angle of radiation pattern, i.e. omnidirectional antennas. One of antenna type that owns circular polarization and omnidirectional radiation pattern is skew-planar antenna.

Skew-planar antenna is modification of cloverleaf antenna [2]. The original cloverleaf antenna basically is loop antenna which is divided into four segments (leaves) to ensure uniformity of current phase along the loop. By employing this method omnidirectional radiation pattern and horizontal polarization as required by FM broadcasting system can be produced. Planar version of cloverleaf antenna (dual polarization) is applied in Canadian Hydrogen Intensity Experiment (CHIME) [3]. Another modification to cloverleaf antenna is by skewing the leaves upward (45º) to produce omnidirectional, circularly-polarized antenna namely skew-planar antenna [4].

With capability to provide circular polarization, omnidirectional radiation pattern, enough beamwidth and gain, as well as small size, skew-planar antenna is popular in UAV community. However, an investigation on the effect of antenna parameters to antenna performance is still needed. This study can lead to design optimization and provide trade-off antenna parameters and performance measures (reflection coefficient (S_{11}), gain, radiation pattern, bandwidth, axial ratio). Section II of this paper presents the effect of tilt angles and coaxial length to the antenna performance ($|S_{11}|$, gain). Second part of this paper (Section III) discusses service distance prediction of this antenna employed in communication between UAV and ground controller.

2. Antenna design and parametric study

2.1. Antenna design

The design of skew-planar antenna is shown in figures 1 and 2. This antenna consists of four elements (leaves) that are tilted at θ degrees and connected to inner conductor and outer conductor of coaxial cable. Lb is the length of straight part of the leaf. La is the length of curved segment of the leaf. Combination of La and Lb produces "φ." Lc is the length of coaxial cable. S is the gap between connected antenna element inner conductor and outer conductor of coaxial cable, D is diameter of copper wire. Lt is length total of element that equal 1 λ at 2.4 GHz which is

$$Lt = 2Lb + La = \lambda \tag{1}$$

For the following parametric study and antenna simulations, coaxial cable RG-316/U is used. The material of the antenna element (leaf) is copper.
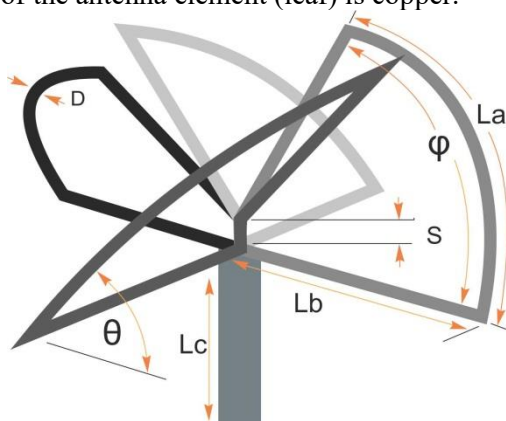

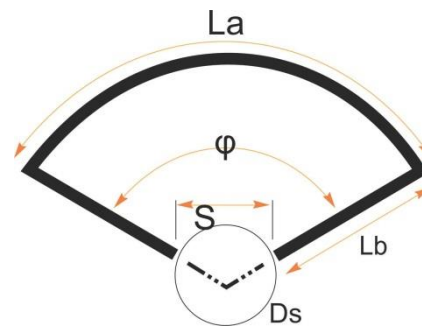**Figure 1.** Design of skew-planar antenna.   **Figure 2.** Detail of a leaf.

2.2. Parametric study

Some parameters have been varied and their effects on antenna performance metrics have been analyzed. The parameters are antenna element angle (φ), antenna element tilt angle (θ), diameter of copper wire (D), coaxial cable length (Lc), and leaf length (Lt). The antenna performance metrics are reflection coefficient ($|S_{11}|$) and gain. In this study, CST Microwave Studio was used.

It is found that skew-planar antenna is very sensitive to leaf tilt angle (θ) and coaxial cable length (Lc), quite sensitive to wire diameter (D), and less sensitive to total length of a leaf (Lt) and leaf angle (φ). With this consideration, results of parametric sweep on θ and Lc are presented here.

2.2.1. Tilt angle (θ). Generally this antenna is designed with $\theta = 45º$ to produce orthogonal electric fields which the same in magnitude; combined with phase difference of 90º circular polarization radiation can be resulted. Figure 3 shows that tilt angle affects reflection coefficient greatly. Varying θ from 35º to 65º shifts the resonant frequency (f_r) in the range of 114 MHz; f_r shifts to low frequency until $\theta = 50º$ (label 5) and then goes to higher frequency. It also affects $|S_{11}|$ at resonant frequencies and their respective bandwidth ($|S_{11}| \leq$ -10 dB). The figure shows that $\theta = 45º$ does not provide widest bandwidth and the best matched at resonant frequency. In term of $|S_{11}|$, $\theta = 55º$ demonstrates the best

matched and bandwidth. Directivity as function of θ is depicted in figure 4 and 5. In the azimuth-cut, this antenna omnidirectional pattern with directivity variation around 0.15 dB. The highest value of directivity owns by θ = 30º and the lowest by θ = 65º, and θ = 55º has value in the middle. The elevation-cut shows similar values except for angle -150º to -100º and 100º to 150º. Considering these facts, tilt angle of 55º (label "6") potentially produce better performance than commonly-known tilt angle (θ = 45º): (a) operational frequency from 2.31 – 2.67 GHz, (b) bandwidth of 360 MHz, (c) maximum directivity of 2.17 dBi, and (d) beamwidth of 113º.
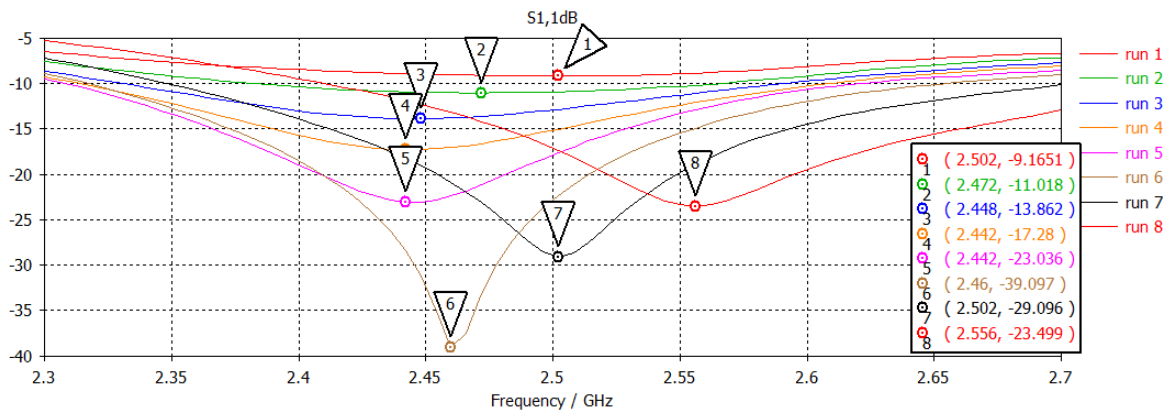
Figure 3. Effect of element's tilt angle variation on reflection coefficient ($|S_{11}|$) values (label "1": 30º, "2": 35º, "3": 40º, "4": 45º, "5": 50º, "6": 55º, "7": 60º, and "8": 65º).
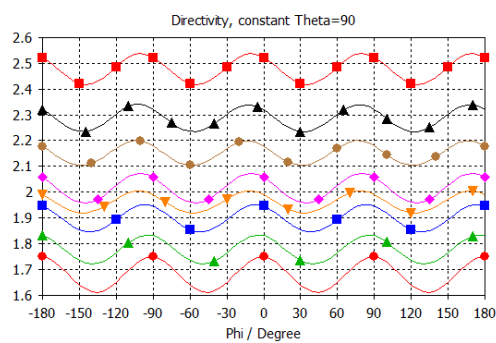
Figure 4. Directivity (dBi, vertical axis) at 2.4 GHz vs. tilt angle at azimuth-cut (labels are the same with Figure 3).
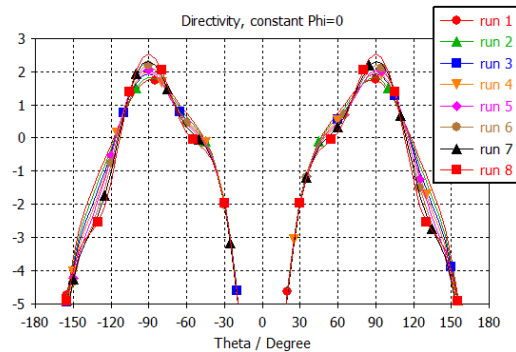
Figure 5. Directivity (dBi, vertical axis) at 2.4 GHz vs. tilt angle at elevation-cut (labels are the same with Figure 3).

2.2.2. Coaxial cable length (Lc). The length variation from 30 to 150 mm shifts the resonant frequency around 100 MHz, see figure 6. Directivity values in azimuth-cut as presented in figure 7 shows that generally the radiation pattern is omnidirectional with variation around 0.2 dB except for length of 150 mm. Combining figure 6 and 7, the best coaxial length setting is 100 mm. Figure shows that the maximum directivity of this length is 2.17 dBi and beamwidth of 113º. This figure also demonstrates that the antenna has doughnut-shaped radiation pattern with nulls at zenith and nadir.

2.3. Proposed design
From the parametric study, combination parameters that produce the best performance in terms of reflection coefficient and radiation are selected, see table 1. As comparison, original design of skew-planar antenna is also presented in the table. Figure 9 compares realized gain, right-hand polarization, in azimuth-cut. It shows that the proposed design ("modified") and original design ("original") has omnidirectional radiation pattern. The modified design has higher realized gain than the original one.

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Figure 10 depicts comparison of realized gain, right-hand polarization, in elevation-cut. The proposed design has stronger radiation at main lobe. Figure 9 and 10 indicate that 3D radiation patterns of both antennas are doughnut-shape.

Reflection coefficient comparison of proposed and original skew-planar is presented in figure 11. The proposed design shows significantly better bandwidth and impedance-match degree compared to the original design. The operational frequency for modified one is 2.313 – 2.712 GHz (bandwidth: 400 MHz) and original one is 2.276 – 2.561 GHz (bandwidth: 290 MHz) hence both antennas are suitable to be used at 2.4 GHz band. The resonant frequency for the proposed design is 2.47 GHz ($|S11|$ = -47.1 dB) and the original one is 2.41 GHz ($|S11|$ = -13.6 dB).

Axial ratio comparisons of both antennas are depicted in figure 12 (azimuth-cut) and figure 13 (elevation-cut). In horizontal-cut, axial ratio of original antenna is around 2 dB and axial ratio of modified one is around 4 dB. It means that the original one is closer to perfect circular polarization than the modified one. Finally, all of these comparisons are summarized in table 2.
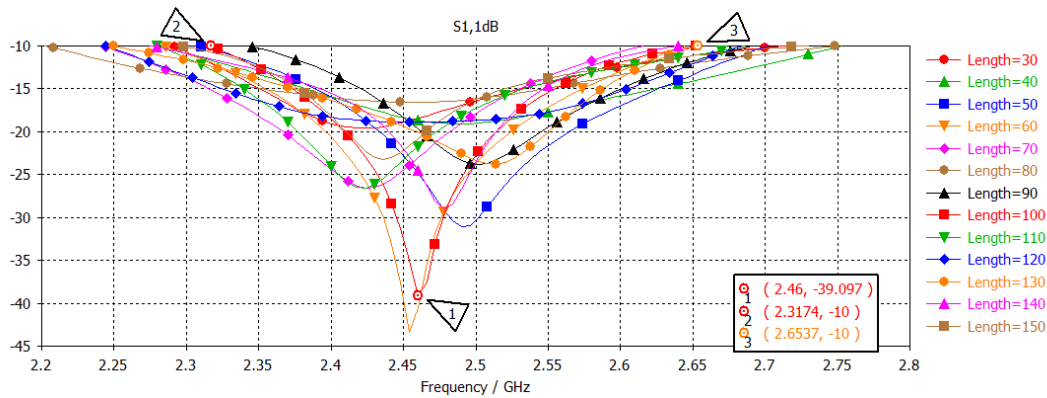
Figure 6. Effect of coaxial length variation on reflection coefficient ($|S_{11}|$) values. The length unit is mm, and $|S_{11}|$ is in dB.
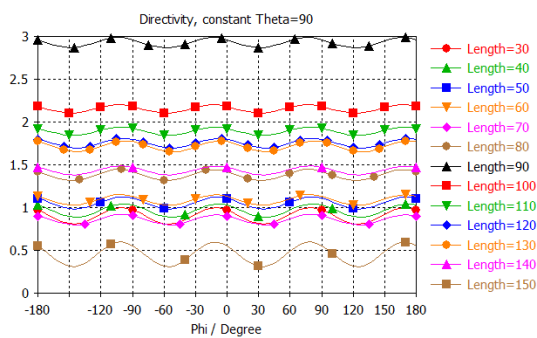
Figure 7. Directivity (dBi, vertical axis) at 2.4 GHz vs. tilt angle at azimuth-cut. The unit of length is mm.
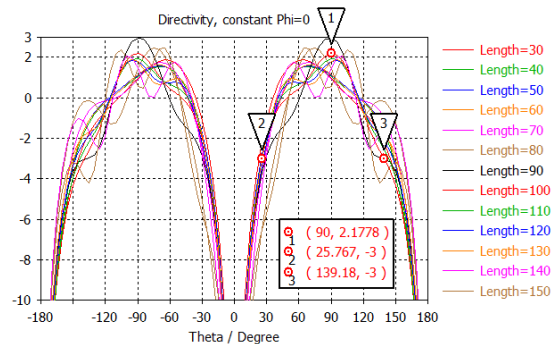
Figure 8. Directivity (dBi, vertical axis) at 2.4 GHz vs. tilt angle at elevation-cut. The unit of length is mm.

3. Prediction of antenna performance in UAV link

Based on the simulation results of the proposed design, service distance of UAV can be predicted. The calculation assumes small-scale fading margin of 6 dB, pointing error loss of 3 dB, gain variation penalty of 2.1 dB, connector and cable loss of 0.19 dB, and the antenna is used in pair with cloverleaf antenna in the link. The predicted service distance employing various communication modules working at 2.4 GHz band is presented in table 3. For low altitude fixed-wing UAV, this antenna can be used with communication module with 16 – 18 dBm transmit power (P_{tx}) and -98 to -100 dBm receiver

sensitivity(S_{rx}) to get more than 2 km service distance. Module with only 100 dB difference between P_{tx} and S_{rx} only capable to provide around 1 km distance. For short distance UAV such as quadcopter, this antenna is enough; however, further distance mission needs the utilization of high gain circular antenna. Skew-planar antenna in pair with 10 dBi axial mode helical antenna can support 10 km distance. Far distance mission uses ground controller antenna which can reach 40 dBi gain [5].

4. Conclusion
The most sensitive parameter of skew-planar antenna is leaf tilt angle and then coaxial length. Modifying the tilt angle to 55º and optimizing other parameters potentially produce wider bandwidth and higher gain, in expense of axial ratio, compared to original design. The proposed antenna is predicted to support service distance of 3 km if employed with communication module which has 18 dBm transmit power and -100 dBm receiver sensitivity. Therefore, this antenna is suitable for fixed-wing UAV.
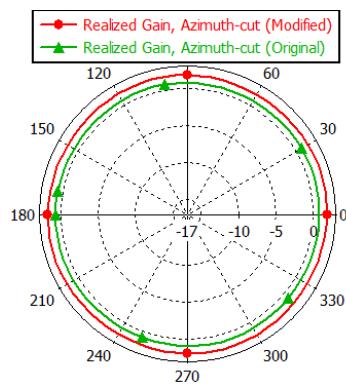
Figure 9. Comparison of realized-gain values, right-hand polarization, azimuth-cut at 2.4 GHz.
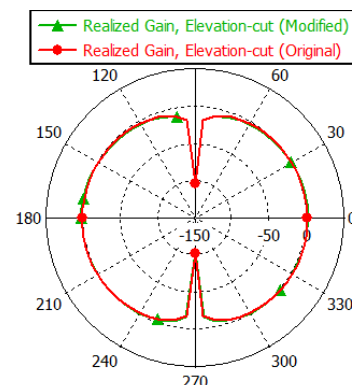
Figure 10. Comparison of realized-gain values, right-hand polarization, elevation-cut at 2.4 GHz.
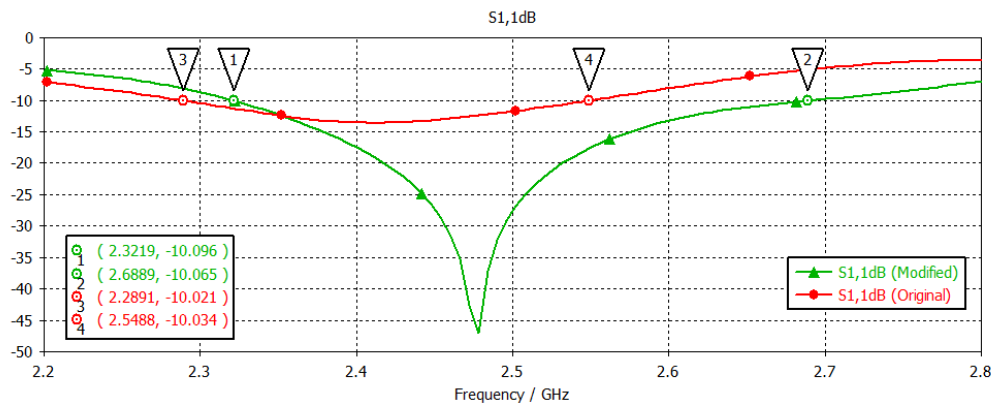

Figure 11. Comparison of reflection coefficient (|S$_{11}$| in dB, vertical axis) values of modified and original designs.
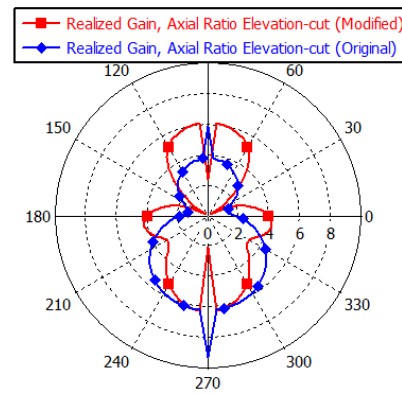
Table 1. Dimension comparison of modified and original designs.

Parameter	Modified Design	Original Design
Leaf length (*Lt*)	125 mm	125 mm
Antenna element angle (φ)	103.4º	108.3º
Antenna element tilt angle (θ)	55º	45º
Length coaxial cable (*Lc*)	100 mm	60 mm
Diameter of copper wire (*D*)	1 mm	0.8 mm
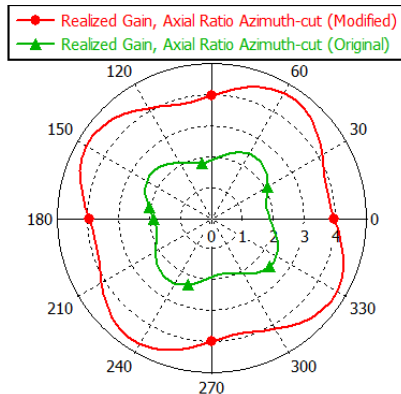
Figure 12. Comparison of realized-gain values, right-hand polarization, azimuth-cut at 2.4 GHz.

Figure 13. Comparison of realized-gain values, right-hand polarization, elevation-cut at 2.4 GHz.

Table 2. Performance metric comparison of modified and original designs.

Performance metric	Modified	Original
Resonant frequency	2.47 GHz	2.41 GHz
$|S_{11}|$ at resonant frequency	-47.1 dB	-13.6 dB
VSWR at resonant frequency	1.0	1.5
Operational frequency	2.313 – 2.712 GHz	2.276 – 2.561 GHz
Bandwidth (VSWR≤2)	400 MHz	290 MHz
Beamwidth (≥-3dB)	110.9º	116.7 º
Gain (main lobe)	1.98 dBi	1.61 dBi
Radiation pattern	Omnidirectional	Omnidirectional
Polarization	Right hand circular	Right hand circular

Table 3. Predicted service distance.

Communication transceiver module	Elevation Angle (º)							
	unit	0	15	30	45	60	75	90
Xbee zigbee s2c	km	1.26	1.07	0.74	0.55	0.36	0.12	0.00
Xbee Pro zigbee s2c	km	3.56	3.03	2.10	1.56	1.02	0.33	0.00
Xbeee Pro Digimesh 2.4	km	3.17	2.70	1.87	1.39	0.91	0.30	0.00
Xbee wifi	km	1.12	0.96	0.66	0.49	0.32	0.10	0.00
DJT Fry Sky telemetry	km	2.45	2.09	1.45	1.08	0.70	0.23	0.00

References

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[4]   ARRL 1964 *The A. R. R. L. Antenna Book* (Newington: American Radio Relay League) p 319
[5]   Alonso JMI and Perez MS 2015 *IEEE Antennas and Wireless Propagation Letters* **14** 771