FINAL RESEARCH REPORT RIGS

Project ID/Title:

PERFORMANCE ENHANCEMENT OF A UWB ANTENNA USING BACKING CAVITY FOR IMPROVED WIRELESS COMMUNICATION SYSTEMS

Project Sponsor:

MOHE

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Abstract:

Ultra Wideband (UWB) is a wireless technology for transmission of massive amounts of data over a wide frequency band using short-pulses with very low power spectral density. In 2002, FCC authorized a frequency allocation in the range of 3.1–10.6 GHz with a maximum transmitted power of -41.3 dBm/MHz for UWB commercial use. Certain applications require unidirectional radiation and thus, antennas are usually backed by either a cavity absorber or a conducting plane reflector. However, the use of absorber will decrease the efficiency to only 50%, while the metal reflector is restricted with a quarter wavelength separation between the reflector and antenna for maximum performance. The objectives of this project is to enhance the performance of wideband antennas for several communication applications which exhibit good radiation patterns with high gain and front-to-back ratio, provide acceptable impedance, with a compact and lightweight structure. The geometrical design of the antennas will be studied and the simulation/design of the antenna will be executed using CST Microwave Studio® (CST MWS). These wideband antennas can be used for military applications such as avionics and microwave direction-finding systems, CubeSat, 5G technologies and other wireless communications e.g. WLAN, WiMAX and Bluetooth, which will be a significant contribution for Malaysia in enhancing its wireless communication.

Key words: Ultra-Wide Band (UWB), Antennas, Archimedean Spiral Antennas, Equiangular Spiral Antennas, Frequency-Independent Antennas, Self-Complementary Antennas, Pattern Symmetry, PEC Reflector, Circular Polarization, Cubesat, 5G, Antenna Array, Linear Polarization, Wideband Antenna, High Gain Antenna, High Impedance Surface (HIS), Liquid Crystals, Monopulse Radar, and Direction-Finding Application.

Introduction:

In 2002, the Federal Communications Commission (FCC) authorized the emission of very low power spectral density in bandwidth, ranging from 3.1 to 10.6 GHz, with maximum EIRP of -41.3 dBm/MHz for UWB communication and localization applications. This action is taken to enable an effective usage on the extremely large frequency spectrum. After the authorization, UWB has become a major interest among researchers, as now the technology can be used in other applications than just military and radar systems. The applications are divided into three major systems; imaging systems (e.g. Ground Penetrating Radar System (GPRS), surveillance system, wall-imaging system, through-wall imaging system and medical imaging system), vehicular radar systems, and communications and measurement systems. This division is done to ensure that UWB devices will not interfere with any other radio services. The fractional bandwidth can be determined by using the following equation;

$$BW = \frac{2(f_H - f_L)}{(f_H + f_L)}$$

where;

f_H = upper frequency of the –10 dB emission point

f_L = lower frequency of the –10 dB emission point

The centre frequency, f_C can be defined by;

$$f_C = \frac{f_H + f_L}{2}$$

Several UWB requirements in frequency domain response include good impedance, radiation and transmission of the antenna. The impedance is measured with a voltage standing wave ratio, VSWR < 2 and return loss, S_{11} < 10 dB. Good radiation performance of UWB antennas includes high radiation efficiency with constant radiation pattern throughout the whole bandwidth, polarization and high gain. Other requirements include having a minimal distortion and an effective isotropic radiated power, EIRP < -41.3 dBm/MHz. UWB have several advantages that make it among the many choice of antenna design. Apart from its high channel capacity and ability to coexist with the conventional communication systems, UWB offers communication security due to its low average power transmission and large bandwidth that makes the signal is seen as noise to other recipient and almost impossible for narrowband to completely interfere the signal. Apart from that, due to its short duration pulses, UWB are more immune to multipath cancellation, and enable its signals to penetrate through many materials.

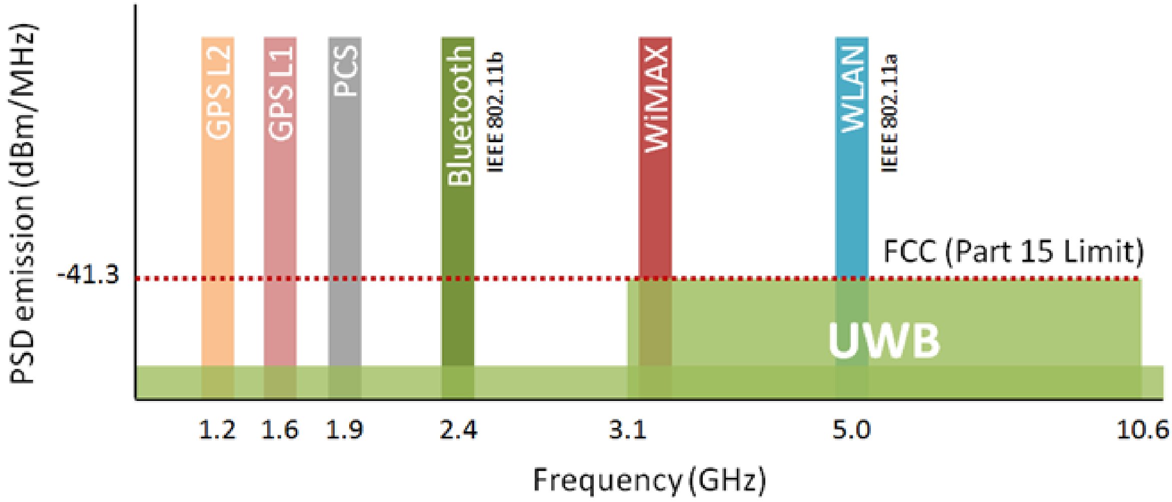

Figure 1. UWB spectrum power spectral density (PSD) emission level authorized by the FCC.

For UWB applications, a fractional bandwidth of ≥20% or a 500 MHz bandwidth regardless of fractional bandwidth is specified by the FCC. This large bandwidth of 7.5 GHz (3.1–10.6 GHz) provides a high data rate even for low SNR in a noisy environment, and is preferable for wireless communication applications e.g. short range high data rate networking. The power spectral density (PSD) is lower compared to other wireless communication systems because of the large bandwidth, and this provides longer battery life for the UWB devices. The combination of very wide bandwidth and very low power level makes UWB signals appear as noise to other recipients and it is almost impossible for narrowband devices e.g. GPS, PCS, Bluetooth, WiMAX and WLAN to interfere (or get interfered) with the signal. Apart from its high channel capacity and ability to coexist with conventional communication systems, UWB systems offer better communication security, with low probability of detection and jamming, due to its low average power transmission. This makes UWB a suitable candidate for high security applications such as military communications. Moreover, these short pulses make them more immune to multipath cancellation and enable its signals to penetrate through many materials. Standard UWB systems require a good impedance match, and this is usually measured using either voltage standing wave ratio (VSWR) or return loss (S_{11}), with typical values of VSWR <2 and S_{11} <-10 dB, respectively.

Antennas are usually backed by a cavity in order to provide unidirectonal direction beam. Antennas with modified ground planes have been proposed throughout the years. In 1986, a log-spiral (equiangular) antenna which is excited against a closely spaced conical ground plane has been built. A foam dielectric is placed between the spiral and the conical ground plane to support the antenna and is fed by a coaxial cable. The distance between the spiral and the conical ground plane is just enough to fit the foam dielectric. Feed point and transition regions are constructed carefully to provide good impedance matching. Due to the conical ground surface, the antenna is able to operate in a much wider bandwidth than a conventional cavity-backed spiral. M. A. Acree et al. has proposed an Archimedean spiral-mode microstrip antenna with a circular dielectric cavity with a conical bottom placed underneath the spiral. The angle between the dielectric cavity and the spiral is customized to get the best result. With the designed dielectric cavity, the antenna is able to provide high gain and an axial ratio similar to the conventional cavity-loaded spiral. In 2009, a spiral antenna built for a satellite boresight reference antenna has been proposed. To provide unidirectional patterns, a stepped ground plane cavity with different quarter wavelength distances at two widely separated frequency bands are placed under the spiral feed. The spiral antenna with the stepped ground plane cavity configuration provides good back lobe suppression with an axial ratio of less than 3dB. The boresight reflector antenna which employs the spiral feed has achieved excellent beamwidth and gain at those two frequency ranges.

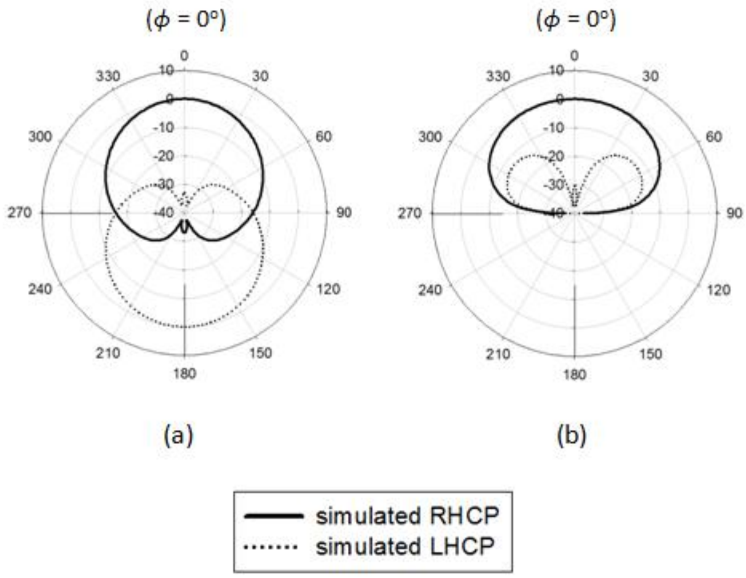

Figure 2. Simulated RHCP and LHCP patterns of antenna (a) in free space (bidirectional radiation), and (b) with cavity backing (unidirectional radiation).

Background:

For many applications, it is desirable to suppress the backlobe radiation of the antenna because electromagnetic scattering from structures in close proximity to the radiating structure can result in pattern ripple and high cross polarization. Moreover, a significant increase in gain can potentially be obtained if a backing structure is used to transform the bidirectional pattern to a unidirectional beam. For planar antennas, this is normally obtained by backing the antenna with a cavity containing an electromagnetic absorber. A major disadvantage of this arrangement is that 50% of the radiated energy is dissipated in the load. For this reason, low-loss metal reflectors have been proposed as a means to simultaneously suppress backlobe radiation and increase the gain of the antenna. A flat metal plate can be used to achieve the optimum radiation characteristics, but only at a single frequency when placed one quarter-wavelength below the radiating aperture. UWB operation is not possible using this simple arrangement because pattern distortion in terms of axial ratio and beam shape are often observed at lower and higher frequencies, respectively, and a large impedance mismatch occurs when the electrical separation between the antenna and metal is small. Previously reported solutions have not produced a satisfactory result to the problems identified above.

Objectives:

The key objectives of this project are;

1. To study and investigate various types of wideband antennas for the use of wireless communications systems (e.g. CubeSat, 5G, microwave direction finding system).
2. To simulate and develop wideband antennas that exhibit good radiation patterns with high gain and front-to-back ratio, and have an acceptable impedance VSWR <2 or return loss S_{11} <-10 dB for improved wireless communication systems.

Methodology:

1. Literature review on wideband antenna will be conducted to gain a full understanding of the project.
2. The geometrical design of the antenna and its feeding techniques will be studied and the simulation and design of the antenna will be executed using CST Microwave

Studio® (CST MWS), with software validation performed at the early stage of research.

3. Parametric studies will be carried out to develop an understanding of the effects of various geometrical design parameters on the antenna radiation performance.
4. Investigating various types of structures for the antenna which are able to provide performance enhancement for the whole structures in terms of gain, axial ratio, pattern symmetry and efficiency. The optimized antenna configuration will be executed using CST MWS.
5. Report write-up and publications; expected output of 4 journal papers – SCOPUS indexed (e.g. Journal of Telecommunication, Electronic and Computer Engineering (JTEC), International Journal of Electrical and Computer Engineering (IJECE), and IEEE Xplore).

Findings:

In the paper "*Performance Comparison between Archimedean and Equiangular Spiral Antenna*", the design and simulation of a two-arm, four turn Archimedean and Equiangular spiral antenna in the frequency range of 1–4 GHz has been performed. The antenna performances such as active region, current distribution return loss S_{11}, gain and radiation pattern of the two spirals have been studied and investigated. Archimedean spiral is said to have a better control of circuitry of radiated signal at low frequency near cut off. This can be seen by the result obtained at 1 GHz, where the return loss of Archimedean is shown to be better, with S_{11} = -24 dB and gain = 2.6 dB, compared to Equiangular with S_{11} = -15 dB and gain = 1.7 dB. Nevertheless, the return loss of Equiangular at this particular frequency is still in the acceptable region of S_{11} <-10 dB. Moreover, the current distribution of the Archimedean is shown to have a distinct and clearer surface current, which makes it easier to detect the exact location of the active region. This characteristic is important if active region is taken into consideration, such as in the design of a conical or a stepped ground plane for wideband spiral antennas. Thus, it can be concluded that the choice of spiral depends on whether an excellent low frequency performance and active region location is required, or researchers can opt for Equiangular design which are simpler and require less number of turns compared to Archimedean.

Next, the paper entitled "*A Modified PEC-Backed Spiral Antenna with Improved Pattern Symmetry*," discussed the pattern symmetry of a two-arm Archimedean spiral antenna which is designed to operate in the UWB frequency range. The analysis is done at three different frequencies; lower frequency f_{low} = 3.1 GHz, center frequency f_{center} = 6.85 GHz, and higher frequency f_{high} = 10.6 GHz of UWB. Spiral antennas exhibit bidirectional radiation pattern with equal energy in both lower and upper hemisphere. A solid PEC ground plane is usually added to provide a unidirectional radiation and high gain. Nevertheless, this degrades the pattern symmetry of the antenna at higher frequencies due to the additional current that exist in the higher order modes region. Thus, the PEC ground plane is modified by inserting circular rings to disrupt the current on the backing cavity. Results have shown that the proposed configuration provide an overall better performance, where the pattern asymmetry has been reduced from 9.0° to 5.8° at 6.85 GHz, and from 56.3° to 35.2° at 10.6 GHz, and still maintain a unidirectional radiation pattern with high gain at the designed frequencies, i.e. 6.44 dBi (6.85 GHz) and 8.54 dBi (10.6 GHz). The proposed antenna configuration can be used in many communication systems such as sensing applications in defense industry, military aircraft, GPS, satellite system, radar system and medical applications, which could potentially provide a wideband performance with symmetrical patterns.

In the paper *"A Wideband Circularly-Polarized Spiral Antenna for CubeSat Application*," the proposed antenna covers two of the commonly used CubeSat frequencies, S-band (2.2 GHz) and X-band (8 GHz). The antenna performances such as return loss S_{11}, axial ratio at boresight (0^0), radiation pattern and gain has been studied and investigated. The proposed Archimedean spiral antenna belongs to the wideband and circular-polarized antenna category. The wideband characteristic can be observed by the S_{11} result where the antenna stays within the minimum limit of less than -10 dB, covering a wide bandwidth from 2.2 GHz to 8 GHz. The antenna also exhibit circularly-polarized radiation with an axial ratio below 3 dB at both 2.2 GHz and 8 GHz. The addition of a cavity backing helps to increase the gain and also change the bi-directional radiation to uni-directional. Moreover, the axial ratio and return loss of the antenna stays within the ideal limit even with the presence of the ground plane. The proposed antenna have met all the requirements set i.e. having a wide bandwidth covering 2.2 GHz to 8 GHz, radiate circular polarization with low axial ratio, and exhibit a uni-directional radiation pattern, and thus will be an excellent choice for a future CubeSat antenna.

Next, the paper entitled "*Study of a Novel Wideband MM-Wave Antenna Array for 5G Applications,"* presents a wideband linearly-polarized printed dipole antenna for the use of 5G applications. The antenna covers six of the potential 5G candidate frequency bands which are 24 GHz, 25 GHz, 28 GHz, 32 GHz, 38 GHz and 40 GHz. The design has been validated by full wave EM simulations. This antenna provides a wide impedance bandwidth of 85.71% in the single element, and a usable bandwidth of 81.48% in the phased array application. The eight elements array implementation enhances both antenna aperture and antenna gain (i.e. realized gain increase from an average of 5.34 dB in the single element, to an average of 12.63 dB in the phased array application). The proposed dipole antenna shows good performance in terms of bandwidth, radiation pattern and gain, which make it a good candidate for future 5G applications.

Finally, in the paper *"Spiral Antenna with Reconfigurable HIS using Liquid Crystals for Monopulse Radar Application"*, a study has been performed to show that an electronically reconfigurable ground plane that consists of a high impedance surface based on liquid crystals can be used to switch between a sum (Σ-) and a difference (Δ-) shaped radiation pattern when this is placed below a two-arm Archimedean spiral antenna. For practical implementation, this can easily be done by varying the voltage between the metal patterned Jerusalem cross slot array and the ground plane, since this produces an electrostatic field in the cavity which controls the orientation of the liquid crystal molecules and hence the permittivity of the tunable material. GT3-23001 liquid crystals with a permittivity and loss tangent of $\varepsilon_{\perp} = 2.5$, $\tan\delta = 0.0143$ is used to model the fully biased case, whereas $\varepsilon_{//} = 3.3$, $\tan\delta = 0.0038$ is used for the unbiased case. Predicted results at 6.5 GHz show that the HIS backed antenna arrangement can be designed to exhibit a deep null (for the Δ-pattern) or a high gain in the boresight (Σ-pattern) direction, when the permittivity of the substrate is changed. The study shows that the HIS should not be designed to operate at resonance ($\phi_{HIS} = 0°$), but at the frequency where $\phi_{HIS} = \pm 90°$, in order to reduce the loss and hence the magnitude of the reflected signals from the backing which is essential in order to provide a Δ-pattern with a deep null. The feasibility study has successfully demonstrated that a very large change in the pattern shape is obtained using this type of reconfigurable HIS.

Conclusion:

As a conclusion, all the project objectives have been met. Studies and investigation of various types of wideband antennas for the use of wireless communications systems (e.g. CubeSat, 5G, microwave direction finding system) has been performed. The antennas has been simulated and developed, and the results has shown that all the proposed antennas exhibited good radiation patterns with high gain and front-to-back ratio, and have an acceptable impedance VSWR <2 or return loss S11 <-10 dB for various types of wireless communication systems.

Output:

Human Capital Development *(PhD, Masters, Research staff with specialty, etc.*)
Masters student:

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   IC/ Passport No. : 930114-14-5808
   Student ID : G1712854
   Level of Study : Masters
   Citizenship : Malaysia
   Year of Graduation : 2018
   Thesis Title : Design and Analysis of a patch antenna for X band in VSAT application

Undergraduate students:

1. Norsyahriani Ibrahim Ooi (IC: 920813-11-5502, ID: 1126484)
2. Nurul Iffarina binti Sulong (IC: 920313-11-5354, ID: 1127494)
3. Ahmad Mujahid bin Ahmad Mustafa (IC: 930315-08-5709, ID: 1317873)
4. Dewan Atiqur Rahman (Passport: AE 4091404, ID: 1221747)
5. Ahmad Alhadi bin Ruslan (IC: 940720-05-5633, ID: 1413573,
6. Nurul Nadia binti Othman (IC: 941228-08-5368, ID: 1416076)
7. Nurul Nazihah binti Ahamad (IC: 941214-11-5706, ID: 1411116)

Publications (International, national, books, chapter in a book, citation, articles, seminar paper, proceedings, etc.):

Five (5) SCOPUS Indexed Journals;

1. Norsyahriani Ibrahim Ooi, Sarah Yasmin Mohamad, Md. Rafiqul Islam, and Nurul Fadzlin Hasbullah (2017). "*Performance Comparison between Archimedean and Equiangular Spiral Antenna." Journal of Telecommunication, Electronic and Computer Engineering (JTEC)*, vol. 9, no.2, pp.105–109 (SCOPUS indexed).

2. Nurul Iffarina Sulong, Sarah Yasmin Mohamad, Md. Rafiqul Islam, and Nurul Fadzlin Hasbullah (2017). "*A Modified PEC-Backed Spiral Antenna with Improved Pattern Symmetry*." *Journal of Telecommunication, Electronic and Computer Engineering (JTEC),* vol. 9, no.3, pp.33–36 (SCOPUS indexed).

3. Ahmad Mujahid Ahmad Mustafa, Sarah Yasmin Mohamad, Norun Farihah Abdul Malek, Farah Nadia Mohd. Isa, and Md. Rafiqul Islam (2017). *"A Wideband Circularly-Polarized Spiral Antenna for CubeSat Application*." *The 4th International Conference on Communication and Computer Engineering (ICOCOE 2017),* 18th - 20th April 2017. Will be published by *Journal of Telecommunication, Electronic and Computer Engineering (JTEC)* (SCOPUS indexed).

4. Dewan Atiqur Rahman, Sarah Yasmin Mohamad, Norun Abdul Malek, Dewan Arifur Rahman, and Siti Normi Zabri (2017). *"Study of a Novel Wideband MM-Wave Antenna Array for 5G Applications." The International Conference on Electrical, Electronic, Communication and Control Engineering (ICEECC 2017),* 5th - 6th December 2017. Will be published by *International Journal of Electrical and Computer Engineering (IJECE)* (SCOPUS indexed).

5. Sarah Mohamad and Robert Cahill (2017). *"Spiral Antenna with Reconfigurable HIS using Liquid Crystals for Monopulse Radar Application." The 2017 IEEE International Conference on Antennas and Applications (IEEE CAMA 2017),* 4th – 6th December 2017. Will be published by *IEEE Xplore* (SCOPUS indexed).

Future Plan of the research:

For the paper *"Spiral Antenna with Reconfigurable HIS using Liquid Crystals for Monopulse Radar Application"*, further work is required to develop this technology, for example to provide a deeper null, smoother radiation pattern and higher gain for the Δ- and Σ-patterns respectively, and the generation of more symmetrical patterns.

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