Investigation of rectangular, uni-directional, horizontally polarised waveguide antennas with longitudinal slotted arrays operating at 2.45GHz

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***Abstract*—Investigations of uni-directional, horizontally polarized waveguide antennas with longitudinal slotted arrays operating at 2.45GHz and their applications to wireless local area networks (WLAN) are presented in this paper. Requirements, considerations, and limitations associated with the design process of this particular waveguide are discussed and presented. Various antenna parameters were simulated using MATLAB® and SuperNEC® software simulation programs, and were applied to a sensitivity analysis of antenna design. End-fed and center-fed antennas were designed, built, and measured at WLAN frequencies. Measured antennas had high gain above 15dBi, broad beam around the azimuth, and high efficiency, but were limited by their impedance dependency and narrow bandwidth. The center-fed antenna had 3dBi higher gain than the 18dBi gain of the end-fed antenna. The VSWR ratio of both antennas was less than 1:1.5 at the operating frequency. The center-fed antenna had broader azimuth and elevation patterns by 40° and 10°, respectively. The end- fed antenna had more stable gain and VSWR, 50% wider VSWR bandwidth of 100MHz, and more directional elevation pattern. The design criteria generated using waveguide theory and simulated analysis was validated by the physical design and performance of the measured antennas.**

***Index Terms*—WLAN, waveguide, slots, array, end-fed, center-fed, free-space wavelength, waveguide wavelength**

I. INTRODUCTION

Since their origin in the early 1940's, waveguide antennas and their applications have evolved from warfare operations and radars to microwave technology and communication systems [1-3]. Today, the introduction of Wireless Local Area Network (WLAN) has allowed microwave technology to penetrate into mainstream applications offering complete network solutions and integrating the operations of many businesses, large institutions, and private users. WLAN operates over the Industrial, Scientific, and Medical (ISM) band ranging from 2.4GHz to 2.5GHz [4],[5].

Indoor and outdoor antennas are used for WLAN applications. Outdoor antennas increase the range of WLAN systems and allow users to access the network from remote locations. These access point antennas provide Point-to-Point and Point-to-Multipoint communication [4].

In concentrated urban areas, there is a need for incorporating many users on a limited number of frequency channels, and minimizing interference from other services and users operating at the same frequency. WLAN antennas need to have a broad beam and the ability to hop across any of the 14 IEEE 802.11b standard designated channels [4]. These access point antennas need to service many users at various locations without interference.

In urban areas many of the antennas are vertically polarized. Horizontal polarization becomes an advantage over large distances and wide area networks, increasing the number of possible users.

Slotted waveguide arrays can be used as access point antennas offering high gain, wide coverage (180° or 360°), and horizontal polarization across the azimuth [5],[6]. This paper investigates the design of these antennas for WLAN applications. The investigations concentrate on rectangular, horizontally polarized, uni-directional (180°) waveguides with longitudinal slotted arrays along their broad walls. The antennas are standing wave fed and support TE_{10} modes. The paper aims to give insight into the capabilities, design tradeoffs, and general characteristics that can be applied to future development of this type of waveguide antenna. The aim was to examine both theoretical and practical antenna properties and their performance at WLAN frequencies. This was achieved through simulation, measurement, and testing of these antennas. This paper presents an overview of waveguide theory, analysis of simulated antenna characteristics and parameters, sensitivity analysis, and comparisons between measured and simulated performances of end-fed and center-fed antenna designs.

II. WAVEGUIDES AND SLOTTED ARRAYS

A. Overview of Waveguide Theory

Waveguides are hollow metal tubes that restrict three-dimensional free-space propagation of electromagnetic waves to a single dimension. These three dimensional structures form a rectangular base along the x-y axis with their length extending along the z-axis. They act as low loss storage devices and contain all field energy with no radiation [7]. Antenna systems need to be incorporated into the waveguide to allow for the radiation of energy contained inside the structure.

1) Wave Motion: Energy inside the waveguide is derived from power inputs that generate travelling fields which deliver high frequency currents, voltages, and power outputs [7]. Power is transmitted by wave motion that is generated by input voltages and currents which compositely exist as a two component, continually moving, electromagnetic field [3],[7],[8]. The electric field (E-field) is a result of the electric potential difference between the sides of the waveguide. The magnetic field (H-field) exists at right angles to the electric field and results from current flow paths along the inside surface of the waveguide. The electric and magnetic fields are voltage and current sensitive conditions respectively. The waves that exist in waveguides can be transverse electric waves, known as TE_{mn} or H_{mn} waves, where the electric field is perpendicular to the direction of propagation, or transverse magnetic waves, known as TM_{mn} or E_{mn} waves, where the magnetic field is perpendicular to the direction of propagation. Characteristic impedance of the waveguide can be considered as the ratio of the transverse electric field to the transverse magnetic field.

The field components are reflected back and forth from the waveguide walls with negligible loss and allow for the wave to proceed forward down the structure [7]. Main horizontally radiated energy is not reflected and does not enter the power transfer situation. Standing waves develop under mismatch or other end conditions as reflections become concentrated at certain maximum and minimum points [7]. Wave front propagation in waveguides is slower than in air as the wave front takes a longer crisscross path, resulting in lower velocity [7]. Waveguides have a defined waveguide wavelength (λ_g), which is related to the frequency of operation inside a waveguide, and which is different from free-space wavelength (λ_o).

A waveguide has a cut-off frequency (f_c) below its operating frequency. The cut-off wavelength (λ_c) and waveguide wavelength (λ_g) are related to each other as shown in the equations below [7],[8],[11],[15]. Subscripts *m* and *n* represent the number of ½λ_o variations along the large (*a*) and small (*b*) inside dimensions, respectively.

$$\lambda_c mn = \frac{2}{\sqrt{\left(\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2\right)}}(m) \tag{1}$$

$$\lambda_g = \frac{\lambda_0}{\sqrt{1 - \left(\frac{\lambda_0}{\lambda_c}\right)^2}} \tag{2}$$

2) Waveguide Modes: Modes are different configurations of the lines of force that define the specific wave composition and the mechanics of wave travel [7],[8]. Each possible electric and magnetic field configuration is called a mode. In the mode configuration in which the electric field lines are all perpendicular to the length of the waveguide a transverse electric (TE_{mn}) field exists [12]. In situations where the magnetic field is perpendicular to the direction of propagation a transverse magnetic (TM_{mn}) mode exists [12].

Different applications require different modes, and the location of the feed along the walls of the waveguide determines the type of mode launched into the waveguide structure. The mode that is simplest to implement and satisfies all frequency requirements is generally used [12].

3) Waveguide Losses: Waveguides act as high pass filters since they transmit only frequencies higher than their cut-off frequency. They operate over smaller bandwidths than transmission lines, but generally exhibit smaller copper, leakage, and dielectric losses, which make them attractive for many applications [7]. The small losses they experience are losses by the signal below cut-off frequency, losses in the dielectric, and losses in the waveguide walls.

4) Waveguide Terminations: Any openings in the waveguide lead to radiation and loss of energy, as a result the open ends of the waveguide need to be closed appropriately. This can be achieved with a short circuited ¼ wavelength stub of transmission line that appears as an open circuit and does not affect impedance [7], [8]. Alternatively, the waveguide can be terminated with a load.

5) Generation of Energy: Power is introduced into the waveguide by waves generated by coupling devices that covert input power from the transmission line into a waveguide mode [7]. A probe or loop may be introduced through an opening located at a non-radiating point on the waveguide where it does not interrupt any currents. A probe excites the electric field and a loop excites the magnetic field [8].

B. Overview of Slotted Array Theory

Energy contained inside a waveguide can be radiated and transmitted by arrays of slots which act as antenna elements along the waveguide. Slots are ideal antenna elements that can easily be incorporated into the waveguide walls without the need for special matching networks that other types of antennas often require. The waveguide structure and the slot arrangement are shown in Figure 1.

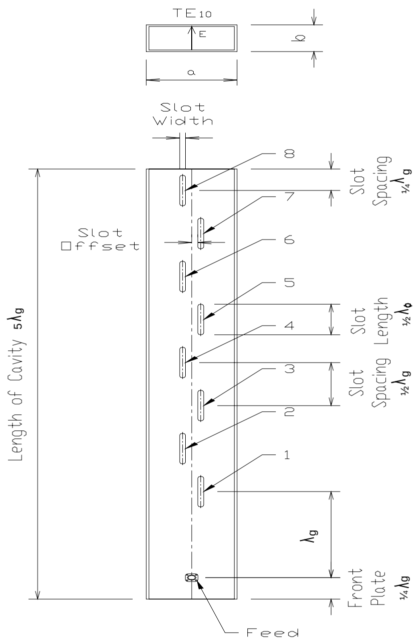

Fig. 1. Diagram of Slotted Waveguide Antenna

1) Slot Operation: A slot in an infinite ground plane is the complement of a dipole in free-space, behaving like a magnetic rather than an electric dipole, since their electric and magnetic fields are swapped [13].

Slots cut in the waveguide walls interrupt the flow of currents and couple power from the waveguide modal field into free-space [7],[8],[12]. When the slots interrupt the current flow lines, the currents move around the slots and give rise to a distortion of the electric and magnetic field patterns inside the waveguide. A voltage difference is set up between the opposite edges of the slots leading to radiation [13].

2) Slot Impedance: The waveguide is a resonant structure and it needs resonant slots [3],[8],[14]. They form purely resistive or conductive loads to the system as their reactance or susceptance vanishes at center frequency [13]. Longitudinal slots represent a shunt load to the dominant wave in the waveguide. The slot is a shunt impedance across the waveguide transmission line or an equivalent admittance loading the transmission line [2],[8]. Stevenson, and later Elliot [1] developed an equation for normalized slot conductance [13],[14] which accounts for the actual slot length and which can be used to calculate slots displacement x.

$$\frac{G_{slot}}{G_{waveguide}} = \left[2.09 \frac{\lambda_g}{\lambda_o} \frac{a}{b} \left(\cos\left(\frac{0.464\, \pi \lambda_o}{\lambda_g} \right) - \cos\left(0.464\, \pi \right) \right)^2 \right] \sin^2 \frac{\pi x}{a} \qquad (3)$$

3) Slot Location: The magnitude of the electric field excitation is proportional to the offset of the slot from center line. The electric field intensity varies sinusoidally across the waveguide cross section and is maximum at the centerline of the broad wall. The position of the slot determines the impedance presented to the waveguide and the amount of energy coupled to the slot and radiated from the slot [13]. A slot in the exact centerline of the broad wall does not radiate, since the electric field is symmetrical around the center of the waveguide and identical at both edges of the slot. As the slot is moved away from the centerline, the difference in field intensity between the edges of the slot increases, more current is interrupted, and more energy is coupled to the slot, increasing radiated power. The sidewalls act as short circuits for the electric field and reduce the radiating properties of the slots. Longitudinal slots far from the center or in the sidewall do not form good radiators [13].

4) Slot Radiation: The ability of a slot to radiate power can be compared to a slot voltage on a transmission line. Slot voltage allows for slots to be modelled as equivalent active shunt admittance on a lossless transmission line.

Slot radiation is contributed to by the forward and backward propagating incident modes and by external mutual coupling from other slots [1],[15]. Slot voltage or radiation leads to forward and backward mode scatter inside the waveguide. Mutual coupling occurs between the slots in an array through the air outside the waveguide [5]. The implication is that mutual coupling contributes to the scattering in the waveguide at a slot, but due to the excitation of a remote slot, complicating the control of the slot excitation [2]. Mutual coupling is large for parallel slots and two dimensional arrays, but is small for the end coupling in linear arrays [8],[15].

5) Types of Slots: Slots can be arranged at varying positions and angles along the waveguide. They can be horizontal, vertical, or inclined, and positioned in the broad or narrow walls [8],[9]. The slots need to be resonant length which is approximately $\frac{1}{2}\lambda_o$. They are generally divided into three types: longitudinal, centre-inclined, and inclined-narrow wall [7],[11]. The simplest and most common is the longitudinal slot. It excites the near electric field transverse to the slots. The electric field is directed across the narrow width of the slot and varies sinusoidally along the length independent of the excitation fields. Resonant length slots can be excited only with a sinusoidal voltage standing wave [7],[9],[12]. The slot direction determines polarization, and vertically oriented slots have horizontal polarization.

6) Resonant and Non-Resonant Arrays: The nature of the wave generated in the waveguide and the type of termination are used to determine if the arrays are resonant or non-resonant [11]. Wave motion inside the waveguide can be in form of travelling waves that lead to a terminating load, or in form of standing waves that are reflected from a short circuit terminating plate and which are set up along the direction of travel.

Resonant arrays are excited by a standing wave [7], the slots are spaced at $\frac{1}{2}\lambda_g$, and the waveguide is terminated with a short circuit spaced at $\frac{1}{4}\lambda_g$ from the center of the last slot. The resulting beam radiates broadside and it maintains its direction with changes in frequency. Standing waves set up a fixed sinusoidal current pattern along the waveguide at a given frequency, and can shift and change the slot excitation when the frequency changes.

Non-resonant arrays are excited by a travelling wave [8], the spacing between the slots can be any length, and the waveguide is terminated with a load. The beam is designed to backfire at an angle to broadside. Travelling waves excite the slots as they pass, and the slots may be placed anywhere relative to the load. The distance between the slots and the propagation constant determine the relative phases. The beam direction is a function of the propagation constant of the wave exciting the slots, and it changes with frequency. Additional beams can be generated by the reflection of the travelling waves from the terminating ends.

7) Slot Arrangement: Spacing of the slots at $\frac{1}{2}\lambda_g$ intervals along the waveguide is an electrical spacing of 180° and each slot is exactly out of phase with the next one in the array. To prevent signal cancellation, slots displacement needs to be alternated around centerline. Slots on opposite sides of the centerline are 180° out of phase, which combined with the existing 180° phase difference results in a total phase difference of 360° between slots, putting them back in phase [13]. When an identical array on the other broad wall of the structure is added, the waveguide becomes omni-directional with a 360° azimuth pattern.

8) Array Feed: The waveguide antenna is connected to a transmitter/receiver device that usually has a coaxial port. A suitable adapter from coaxial line to waveguide must be constructed and integrated into the antenna. A coupling probe is inserted at $\frac{1}{4}\lambda_g$ from the shorted end and at a depth of $\frac{1}{4}\lambda_o$ so that the action of the probe is similar to that of a monopole [14]. In order to permit radiation in one direction along the guide a reflecting plunger is placed $\frac{1}{4}\lambda_g$ from the feed antenna.

The length of the feed, its distance from the short circuit and its position along the broad wall influence the load presented to the coaxial line. This load is made up of radiation resistance and reactance, and it presents a load impedance to the coaxial cable and an admittance to the dominant mode in the waveguide [9]. Correct position of the feed allows the backward propagating modes to reflect and add constructively with the forward propagating modes, launching TE_{10} mode power into the waveguide.

Generally, the array is designed so that at working frequency there is no backscatter of energy to the feed and there is no return loss [15]. Some backscatter from the array always occurs at frequencies different from the operating frequency [1],[15].

III. Simulated Antenna Analysis

A. Overview of Simulated Antenna Analysis

Theoretical analysis and software simulations aid the investigations of antenna behaviour and help identify important parameters and limitations that would be difficult to find during measurement. SuperNEC® [16] was used to simulate the antenna structure and perform a sensitivity analysis of the antenna parameters and overall performance [17],[18].

TABLE I
Dependence of Antenna Properties

	*Large ID**	*Small ID**	*Slot Length*	*Slot Offset*	*Slot Width*	*Slot Spacing*	*Slot Number*	*End Plate*	*Front Plate*	*Feed Location*	*Feed Length*	*Feed Width*
*Large ID**	X	X	X	X						X		
*Small ID**	X	X									X	
Slot Length	X		X	X	X	X						
Slot Offset	X		X	X	X	X				X		
Slot Width	X		X	X	X	X				X		
Slot Spacing	X					X		X	X	X		
Slot Number							X	X	X	X		
End Plate								X	X	X		
Front Plate								X	X	X		
Feed Location	X									X	X	X
Feed Length		X								X	X	X
Feed Width	X	X								X	X	X

* ID refers to the internal dimensions of the waveguide cross-section

The design of any slotted waveguide array is an amalgamation of two individual antenna theories, one concerned with the waveguide characteristics and the other with slots and slotted arrays. Waveguide influences the type of wave passing through the structure and the frequency at which the antenna operates. The slots influence the manner in which the energy is manipulated i.e. radiated or absorbed.

Table I shows the relationship between various antenna parameters and how they relate to each other [17]. Analysis of simulated antenna performance was used to identify these relationships. The crosses indicate dependence between parameters, implying that a change in one parameter can induce changes in other parameters and hence the antenna performance. Large cross sectional dimension of the waveguide, the type and location of the feed, the number and size of the slots, and the slot offset were found to be the main parameters with most impact on the both physical characteristics and performance of the antenna. These relationships need to be considered when developing optimal designs and satisfying various requirements.

B. Investigations of the Waveguide Characteristics

1) Frequency of Operation: As in any antenna design, the most vital consideration is the frequency of operation, which determines λ_g and λ_o. All dimensions related to the waveguide are described in terms of λ_g, and all dimensions related to the slots are described in terms of λ_o. The factors that affect the operating frequency of the antenna are the waveguide dimensions, slot length and spacing between the slot centers, and the length of the feed. Table II shows all frequency and wavelength requirements.

TABLE II
ANTENNA FREQUENCY REQUIREMENTS

	Waveguide
Frequency Range (GHz)	2.4 - 2.5
Center Frequency (GHz)	2.45
Free-space Wavelength λ_o (mm)	122.36
Waveguide Wavelength λ_g (mm)	161.2
Cut-Off Frequency (GHz)	1.59
Cut-Off Wavelength λ_c (mm)	188

2) Waveguide Dimensions: Waveguide cross-sectional dimensions influence the frequency range of the antenna, and the resonant and cut-off frequency. They also influence the propagation and attenuation of the wave, and determine the slot conductance and radiating ability [12].

The number of half wave period variations of the electric field for the TE waves or the magnetic field for TM waves, is determined by the height and width of the waveguide, respectively. They also determine the mode that the waveguide supports.

Width of the waveguide determines the operating frequency and it forms the limits of frequency bandwidth. Any changes in width cause a shift in the operating frequency of the waveguide.

Simulations have shown that the width can be extended or decreased by $^1/_{16}\lambda_g$ without affecting the antenna performance and frequency bandwidth. When the width is decreased below $^1/_{16}\lambda_g$ the antenna shifts to a higher frequency range and lower frequencies are cut off. When the width is increased above $^1/_{16}\lambda_g$ the antenna shifts to a lower frequency range and higher frequencies are cut off.

Height of the waveguide has less influence on the antenna operation and is therefore a more flexible parameter. However it needs to be less than $½\lambda_g$ to ensure correct mode of operation and to keep the rectangular shape of the structure.

Thickness of the waveguide walls is a parameter that is often overlooked, and it needs to be kept as small as possible since thick walls can lead to field distortions. The ratio between the wall thickness and the width needs to be smaller than 1:30.

3) Position of End Plate: The end plate needs to be located at odd multiples of $¼\lambda_g$ or $⅛\lambda_g$ from the center of the last slot. Placement of the end plate at multiples of $½\lambda_g$ or $1\lambda_g$ causes wave cancellation and inhibits radiation. The distance between the last slot center and the end plate can be varied. Increasing this distance causes an initial improvement in VSWR and gain, but distance greater than $¾\lambda_g$ causes no further improvement in antenna behaviour.

4) Position of Front Plate: The distance of the front plate to the center of the first slot is a combined distance from the feed and the front plate, and from he feed and the center of the first slot. The distance of the feed from the center of the first slot needs to be a multiple of $½\lambda_g$ or $1\lambda_g$. If this distance is increased too much it causes the VSWR to increase.

C. *Investigations of the Slotted Array Characteristics*

1) Number of Slots: The number of slots forms the vertical aperture of the antenna and influences the gain and the radiation pattern. As the number of slots increases, the gain increases and the VSWR and frequency bandwidth improve. Simulation results showed that the gain increase is more pronounced initially, and it stabilizes from 2.5dBi to 1dBi as more slots are added. This verifies array theory which states that gain increases by 3dBi as the number of slots doubles. The array size needs to be kept greater than 4 slots as the simulated results have shown that the antenna with fewer slots has unstable gain and VSWR characteristics.

The increase in gain is accompanied by the flattening of the vertical beam and narrowing of the elevation pattern [13]. As the number of slots increases, the number and magnitude of the side lobes increases. Large waveguides have more side lobes and more wasted energy into space.

Infinite increase in the number of slots is inhibited by attenuation within the waveguide, increasing side lobe levels, and eventual saturation of the gain curve. Practical implementation of a large waveguide becomes too laborious as the structure becomes too long and heavy, difficult to mount, and impractical to build.

2) Slot Length: Slots need to be narrow and approximately $½\lambda_o$ long to ensure that the distribution of the electric and magnetic fields along them is sinusoidal [1]. Simulations have shown that the slot length can be extended or reduced by $\frac{1}{25}\lambda_o$ without interfering with the frequency of operation. Decreasing the slot length shifts the operation to a higher frequency, and increasing the slot length shifts the operation to a lower frequency. The resonant length of the slot is affected by the position of the slot along the waveguide, its displacement from centerline, slot width, and the frequency of operation.

3) Slot Width: The slots need to be narrow and their width small compared to their length. If the slot width becomes too wide it begins to act as an aperture and it can interrupt currents in two coordinate directions. From the simulated results it can be deducted that the ratio of slot width to its length should be 1:9.

Slot width is dependant on the slot displacement from centerline, and it can affect the slot conductance and cause mismatch with the system. Small offsets require narrow slots, and bigger offsets require wider slots. Simulations have shown that each offset has a certain slot width limit after which the slots will not operate. Small offsets require widths smaller than $^1/_{20}\lambda_g$, and bigger offsets require limits smaller than $^1/_{10}\lambda_g$ [17]. When there is no slot offset and the slots alternate around the centerline the slots need to be wider than $⅛\lambda_g$.

4) Slot Displacement from Centerline: Slot displacement from centerline is an important but volatile parameter. Slots should be placed close to the center of the broad wall as displacement far from the center or in the sidewall will not lead to significant radiation. Slot offset greater than $^1/_6\lambda_g$ does not cause any radiation since the slots are too close to the short circuiting sidewalls [17]. Simulations have shown that smaller slot displacements result in greater gain bandwidth and higher cut-off frequency, and larger slot displacements result in narrow gain bandwidth and lower cut-off frequency. The greater the offset, the more mismatch with the system occurs.

5) Spacing between Slot Centers: A resonant array requires ½λ_g spacing between the slots. If this spacing is changed it causes a shift in the operating frequency. An increase in the spacing shifts the antenna to lower frequencies and a decrease in the spacing shifts the antenna to higher frequencies. This distance between slot centers needs to be accurate to ensure that the antenna operates properly. Simulations have shown that it can sustain variations of $^1/_{20}\lambda_g$ in either direction [17], but anything more than that will result in a non-functional antenna.

D. Investigations of the Antenna Feed

1) Feed Length: The feed is a monopole probe and as such changes in the probe length shift the operating frequency of the antenna. The depth of the probe assists in matching the impedance between the coaxial line and waveguide. The VSWR becomes distorted for lengths that are too long or too short [17].

2) Feed Diameter: Although a feed with a wide diameter tends to increase bandwidth, a small diameter feed is more suitable at this frequency. Simulations have shown that the ratio of feed diameter to its length should be 1:15.

3) Feed Location: The feed needs to be placed at odd multiples of ¼λ_g or ⅛λ_g from the front plate of the waveguide. When the feed is located at odd multiples of ⅛λ_g it has a wider impedance and VSWR bandwidth [17]. Feed locations at multiples of ½λ_g or 1λ_g result in a signal that is not launched and reflected properly resulting in a non-radiating antenna.

The feed can be located between two successive slots along the waveguide. This type of feed location results in narrow, concentrated VSWR and frequency bandwidth. As the feed location moves up the waveguide, the frequency shifts to higher frequencies and the gain drops by 7dBi as the length increases. Feed located in the center of the array is most effective. The spacing between the slot centers needs to be kept at ½λ_g. Incorrect location of the feed between two slots inhibits antenna radiation.

E. Simulated Results

Table III shows the sensitivity and the range of antenna parameters over the operating frequency band [17]. The minimum and maximum values form the limits of each parameter, and any deviation from these limits results in poor antenna performance. These values are represented in physical lengths and in terms of the relevant wavelength. The aim of this table was to provide a reference with a summary of parameter ranges and tolerances that may be used for the design of this type of antenna.

TABLE III
RANGE OF ANTENNA PARAMETERS AT 2.45GHZ

	Range		*Minimum*		*Maximum*	
	Length	*λ*	*Length*	*λ*	*Length*	*λ*
Waveguide						
Long ID	10	$0.08\lambda_o$	84	$0.69\ \lambda_o$	104	$0.85\ \lambda_o$
Small ID	20	$0.16\ \lambda_o$	24	$0.20\ \lambda_o$	64	$0.52\ \lambda_o$
Wall	4	$0.03\ \lambda_o$	1	$0.01\ \lambda_o$	5	$0.04\ \lambda_o$
Location of shorting plates from the center of the nearest slot						
Front	241.8	$1.50\lambda_g$	80.6	$0.50\ \lambda_g$	322.4	$2\ \lambda_g$
End	423.15	$2.63\ \lambda_g$	763.25	$4.7\ \lambda_g$	1186.4	$7.35\ \lambda_g$
Slots						
Number	31		5		36	
Length	10	$0.08\ \lambda_o$	52.3	$0.43\ \lambda_o$	62.3	$0.51\ \lambda_o$
Width	6	$0.05\ \lambda_o$	2	$0.02\ \lambda_o$	8	$0.07\ \lambda_o$
Offset	9	$0.06\ \lambda_g$	8	$0.05\ \lambda_g$	17	$0.11\ \lambda_g$
Spacing	10	$0.06\ \lambda_g$	75.6	$0.47\ \lambda_g$	85.6	$0.53\ \lambda_g$
Feed						
Length	15	$0.12\ \lambda_o$	22	$0.18\ \lambda_o$	37	$0.30\ \lambda_o$
Width	2	$0.02\ \lambda_o$	2	$0.02\ \lambda_o$	4	$0.03\ \lambda_o$
Location along the waveguide						
End	120.9	$0.75\ \lambda_g$	18.1	$0.11\ \lambda_g$	120.9	$0.75\ \lambda_g$
Center	322.4	$2\ \lambda_g$	219.2	$1.35\ \lambda_g$	541.6	$3.35\ \lambda_g$

* ID refers to the internal dimensions of the waveguide cross-section

IV. COMPARISON OF END-FED AND CENTER-FED ANTENNAS

Investigation into the operation of slotted waveguide antennas requires practical analysis in form of design, construction, and measurement. End-fed and center-fed antennas were developed and measured in an anechoic EMC chamber [19]. Simulated analysis was used to generate the best antenna designs and to verify the measured performance [20].

A. Antenna Design and Construction

The approach to the design and construction of antennas built and measured incorporated waveguide theory, physical constraints and simulated analysis [17]. The aim of the measurements was to use the above mentioned design approach and simulated analysis to identify optimal waveguide parameters and verify them through measurements. The investigation was focused on uni-directional waveguides with longitudinal slots operating at WLAN frequencies. Two types of antenna designs were chosen for measurement. The antennas had the same structural design, with the only difference being the location of the feed, one was end-fed and the other one center-fed [21]. The simulated results provided a comprehensive investigation of the effect of variations of physical parameters of the waveguide and the slots, and required no further analysis but were useful in identifying optimal parameters. As a result, a different feed location was chosen as a varying parameter since it allowed investigations of two different application of waveguide theory.

The operating frequency of the antenna was used to determine all physical dimensions of the waveguide and the radiating slots. Standard sized aluminium rectangular tubing with 94mmx44mm inside dimensions and 3mm wall thickness [21] was chosen in order to keep the amount of welding at a minimum and to reduce the risk of any distortion of the fields and losses in the waveguide.

The simulated results were used as guidelines for the various slot parameters. The slot length was kept at $½\lambda_o$ (53mm) according to the waveguide theory, while the slot width was calculated to be 6.5mm using the 1:9 width-to-length ratio that was identified using the simulated results. A 10mm slot displacement was calculated according to the simulated results which showed that smaller slot displacements result in greater gain bandwidth and higher cut-off frequency.

The practical limitations of the equipment used to cut and drill the metal structure of the waveguide and the slots, had to be accounted for and the lengths and sizes were rounded off to a dimensions that could be calculated, measured, and cut in the laboratory using the available equipment.

Simulations had also shown that although the gain increases as the number of slots increases it stabilizes after a certain number of slots and further additions of new slots only increase the physical size of the waveguide and the number of sidelobes. The simulation of an 8-slot design showed a stable 15dBi gain, VSWR ratio less than 1:2, and a broad and symmetrical radiation pattern.

A simple monopole feed was used in all designs and according to dipole theory the length was $0.25\lambda o$ or 31mm [21]. A feed with a 2mm diameter was calculated using a 1:15 ratio of diameter-to-length that was calculated using the simulated results. The simulations also indicated that a smaller diameter feed would be more effective for this type of design.

The spacing between slot centers and the location of the end plates was calculated according to the waveguide theory that states that a resonant array requires $½\lambda_g$ spacing between the slots.

The waveguides were designed to support TE_{10} mode which was launched with the appropriate positioning of the feed in the center of the broad wall. The monopole feed was made form copper wire and an N-type female connector was used for the coaxial-antenna conversion.

B. Comparison between the Simulated and Measured Antenna Performance

Simulated results shown in Table IV indicate that the end-fed antenna has 15 dBi gain which is 2dBi more that the center-fed antenna.

TABLE IV
SIMULATED ANTENNA PERFORMANCE

	End-Fed	*Center-Fed*
Gain (dBi)	15	13
VSWR	2.5	2.5
VSWR Bandwidth (GHz)	2.2-2.52	2.42-2.52
Impedance (Ω)	80	38
Gain Ratio (F/B Ratio) (dB)	8.625	9.15
Efficiency (%)	100	100
Radiated/Input Power (W)	0.008	0.01
Return Loss (dB)	7	7

The end-fed antenna also has a more symmetrical elevation pattern. The two antennas have a 1:2.5 VSWR ratio and good efficiency. The end-fed antenna has a 3 times wider VSWR bandwidth of 320 MHz, compared to a VSWR bandwidth of 100 MHz of the center-fed antenna. It also exhibits a lower front-to-back (F/B) ratio [20]. The two antennas have the same VSWR ratio and therefore their differentiating factors are gain, bandwidth and horizontal radiation. The end-fed antenna performs better with a higher gain of 15dBi and a wider bandwidth of 320 MHz.

The radiation patterns in the azimuth and elevation planes of the end-fed and center-fed designs are shown in Figure 2. and Figure 3., respectively.

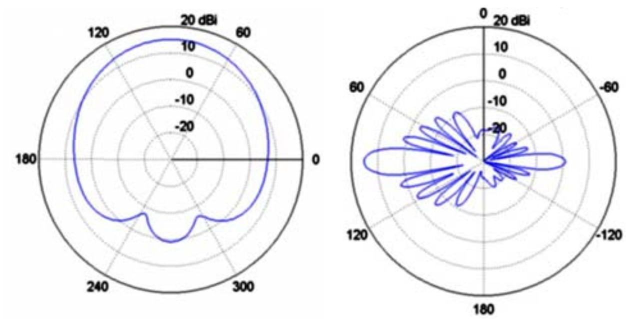

Fig. 2. Simulated azimuth and elevation radiation patterns of the end-fed slotted waveguide antenna

Both antennas have a broad azimuth pattern; however the end-fed antenna seems to be more directional which is reflected in both its azimuth and elevation patterns. Overall, the end-fed antenna exhibits narrow, symmetrical and directional radiation patterns. This type of radiation pattern is suited for access-point antennas that require precise direction. The azimuth pattern of the center-fed antenna is more circular while the main lobe of its elevation pattern is 10° wider than the 12° main lobe of the end-fed antenna. This type of antenna could be used in application where the number of users along the horizon takes precedence over the directivity of the antenna to a more concentrated number of users.

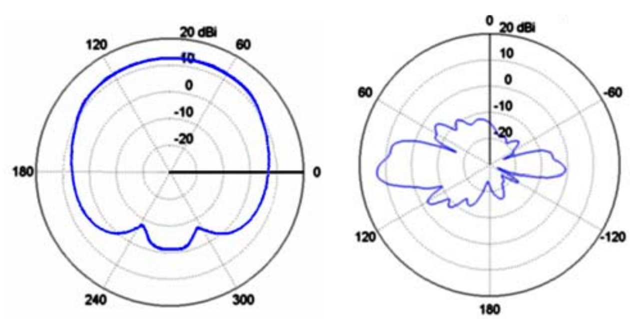

Fig. 3. Simulated azimuth and elevation radiation patterns of the center-fed slotted waveguide antenna

Measured antenna properties show a difference in the gain characteristics. Figure 4. shows an increase in gain by 4dBi and 7dBi for the end-fed and the center-fed antennas, respectively. The measured results also shown an improvement in the VSWR ratio which decreases from 1:2.5, as shown in Figure 5. The end-fed antenna has a stable and constant 1: 1.5 VSWR. The center-fed antenna has higher VSWR in the lower channels and a lower VSWR reaching 1: 1.2 in the higher channels of the operating frequency range. This verifies the simulated results which indicate that the end-fed antenna has a wider VSWR bandwidth. The simulated results were measured over a wider frequency band 2.36-2.56GHz and hence the end-fed antenna shows a 3 times wider bandwidth than the center-fed antenna, analysis of the measured results between 2.4-2.5GHz indicates that the end-fed antenna has 2 times more bandwidth than the center-fed antenna.

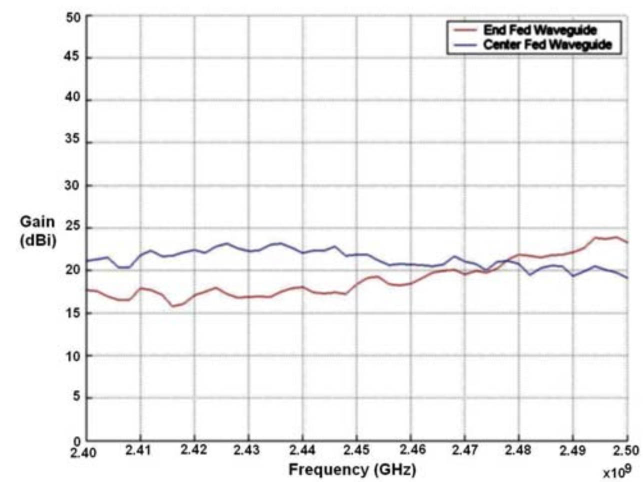

Fig. 4. Measured gain of the end-fed and center-fed slotted waveguide antennas

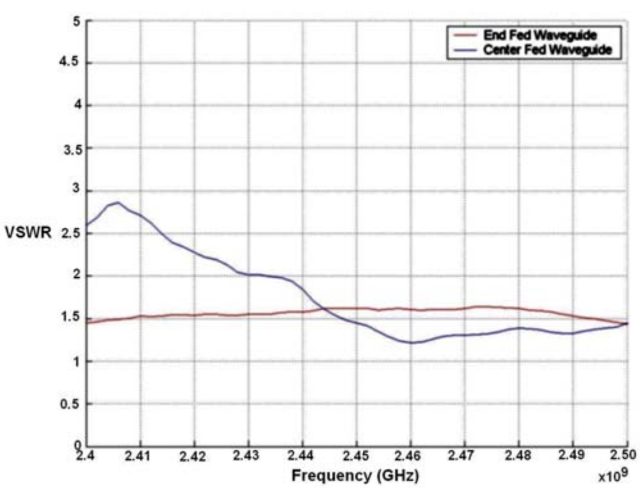

Fig. 5. Measured VSWR of the end-fed and center-fed slotted waveguide antennas

The measured azimuth and elevation radiation patterns of both antennas are shown in Figure 6. and Figure 7., respectively [22]. There is a 2dBi discrepancy in the azimuth and elevation patterns of the center-fed antenna and it is expected that this is a result of inaccurate measuring instruments and losses experienced in the laboratory. However, the simulated and measured radiation patterns both indicate that the center-fed antenna has a broader beam, while the end-fed antenna is more directional with a narrower elevation beam. What is interesting is that measurements show that a centre-fed antenna has a higher gain than the end-fed antenna, with a broader radiation pattern. This is the key difference between the simulated and measured results. This type of behaviour seems to contradict basic antenna fundamentals, however it is expected that due to the unique nature of waveguides and particular design and feed of a center-fed antenna the theory might not apply as in a classic antenna design.

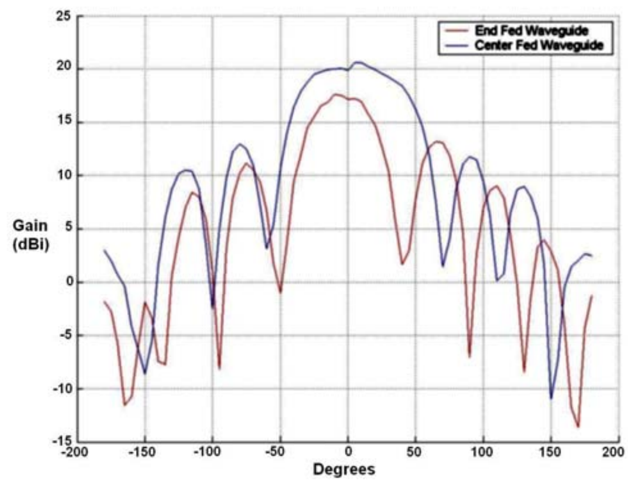

Fig. 6. Measured azimuth radiation pattern of the end-fed and center-fed slotted waveguide antennas

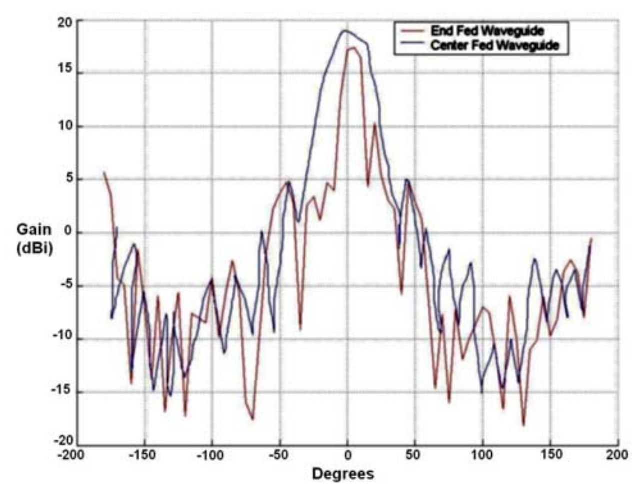

Fig. 7. Measured elevation radiation pattern of the end-fed and center-fed slotted waveguide antennas

The analysis of the two antennas clearly highlights that these types of waveguide antennas used for WLAN application exhibit high gain of more than 15dBi. The VSWR characteristics of the two antennas are less than 1:2 and the end-fed antenna has a wider bandwidth of 100MHz, which is twice the bandwidth of the center-fed antenna across the 2.4-2.5GHz frequency band. Both antennas have a broad azimuth pattern highlighting their potential for access point applications for many users. The end-fed antenna has a more narrow elevation pattern making it more directional along the horizon. The wider elevation pattern of the center-fed antenna indicates that the antenna might pick up signals that are vertically polarised. This property can be worked on to create an antenna that can pick up both horizontal and vertical signals from single position; otherwise the antenna might become prone to interference in a physical environment. The end-fed antenna has almost two times more bandwidth than the center-fed antenna, while the center-fed antenna in turn has better gain and VSWR ratio over its more concentrated bandwidth. These two characteristics could be used for applications that require more frequency coverage or more users with different frequencies in the case of the end-fed antenna, or for applications that require a specific frequency and fewer users within that band in the case of a center-fed antenna. Overall, it can be concluded that the characteristics of the two antennas could be applied to both Point-to-Point and Point-to-Multipoint communication.

C. *Measured Results*

Table V is a summary of the measured performance of the end-fed and center-fed waveguide antennas.

TABLE V
MEASURED ANTENNA PERFORMANCE

	End Fed	Center Fed
Horizontal Polarization		
Gain (dBi)	18	22
VSWR	1.5	1.4
VSWR Bandwidth	2.2-2.63	2.4-2.65
Impedance (Ω)	44.06	43.28
Vertical Rejection (dBi)	23	24
Vertical Rejection Gain (dBi)	-5	-2
Vertical Polarization		
Gain (dBi)	18	22
VSWR	1.5	1.4
VSWR Bandwidth	2.2-2.63	2.2-2.65
Impedance (Ω)	44.06	43.28
Horizontal Rejection (dBi)	23	24
Horizontal Rejection Gain (dBi)	-5	-2
Radiation Pattern		
Azimuth		
Gain (dBi)	18	21
Maximum Sidelobe Level (dBi)	15	17
Minimum SIdelobe Level (dBi)	3	7
Between First Nulls (°)	100	137.5
Half Power (°)	70	95
Elevation		
Gain (dBi)	18	19
Maximum Sidelobe Level (dBi)	4	3
Minimum SIdelobe Level (dBi)	-10	-10
Between First Nulls (°)	30	40
Half Power (°)	15	17

Measurements were also used to investigate the performance of the antennas under vertical polarization. It can be seen that both antennas support horizontal and vertical polarization equally well, as shown in the table. Both antennas are good at rejecting oppositely polarized signals by up to 24dBi. Simulated and measured performances of these antennas are presented in [20] and [22], respectively.

V. CONCLUSIONS

In this paper, design criteria and limitations associated with the application of slotted waveguide antennas for WLAN, were investigated. The paper focused on a specific type of uni-directional horizontally polarized waveguide antennas with longitudinal slots. These antennas were researched and the theory behind their operation was presented. Properties and characteristics of the waveguide resonant cavity, slotted array antenna, and the feed system were simulated using SuperNEC®, and their influence, range, and effect on the antenna performance identified.

All simulated results were classified and combined to form a set of parameter ranges that can be used when designing this type of antenna for WLAN.

These simulated guidelines were used as aids in the design and construction of two antennas that were measured in the laboratory to provide measurements and indication of the antenna operation and performance at WLAN frequencies in a physical environment. The two antennas had the same structural design and were uni-directional with 8 slots running down one side of the waveguide [21], with the only difference being the location of the feed [21].

End-fed and center-fed antenna designs were simulated, constructed, and measured in the laboratory. Measurements showed that both antennas have high gain and low VSWR. The gain of the end-fed and center-fed antennas was 18dBi and 22dBi, respectively. They had an average VSWR ratio of 1:1.5. The center-fed antenna had a 40° broader azimuth pattern, while the end-fed antenna was more directional in the elevation plane. The end-fed antenna had a stable and consistant VSWR ratio of 1:1.5 over the measured frequency bandwidth of 100MHz across the 2.4-2.5GHz band. The center-fed antenna had a lower VSWR ratio which averaged 1:1.2 over a more narrow bandwidth of 50MHz.

The investigations indicated that SuperNEC® simulations of waveguide antennas take a long time and are exhaustive of the computational ability of SuperNEC®. The waveguide structure that has many thousands of segments that require many hours of computational time and additional memory. This slows down the design process and should be considered when designing this type of antenna. However, design curves and simulated analysis presented in this paper should aid and speed up the design process and should reduce some of the time spend on future designs. It is expected that discrepencies in gain and VSWR between simulated and measured results were a direct result of this issue. However, simulated results were effective in describing the behaviour and performance of the antenna under varying conditions.

Overall, this paper has presented an overview of the operation of a particular type of waveguide antenna and has presented investigations of various parameters and their effect on the operation of the antenna at WLAN frequencies. This paper has also shown simulated and measured performances of these antennas and had verified that they can be successfully used in WLAN applications.

The investigated waveguide antennas were found to be able to handle high power gain with high efficiency. They guide and transmit wave energy with few losses, and need simple monopole feed systems that require no special matching networks to the slotted arrays. Their limitation is that they are impedance dependant, resonant structures, and as such they are narrow band. They are bigger in size and mass compared to other antennas operating at the same frequency, but their size offers mechanical ruggedness and built-in lightning protection. They have a broad azimuth pattern and are highly directional in the elevation plane. They work equally well when horizontally or vertically polarized, and successfully reject opposite polarization. Their bandwidth is sufficient for WLAN applications, and they can be ideal access point antennas.

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