ISSN 0511-5728
The West Indian Journal of Engineering
Vol.37, No.2, January 2015, pp.14-22

Exploring Potential RF Hot Spot Locations in Confined Spaces of Large Wave Guide Dimensions

Ricardo J. Rodriguez [a,Ψ], and Winston G Lewis [b]

Department of Mechanical and Manufacturing Engineering, Faculty of Engineering, The University of the West Indies, St Augustine, Trinidad and Tobago, West Indies
[a]E-mail: ricardoj.rodriguez@yahoo.com
[b]E-mail: winston.lewis@sta.uwi.edu

[Ψ] - Corresponding Author

(Received 8 April 2014; Revised 15 August 2014; Accepted 05 October 2014)

Abstract: *Radio-Frequency (RF) waves belong to the non-ionizing region of the electromagnetic spectrum and as such do not possess sufficient energy to ionize particles. They may however cause heating especially of human tissue which can therefore render them a potential hazard for workers and the public at large. International authorities have recognised the potential threat and have developed RF exposure guidelines to ensure some level of safety. These guidelines are developed for the electromagnetic spectrum but with a special interest in the Specific Absorption Rate (SAR) region (i.e., 30 to 1,000 MHz) where the strictest limits are set. In this part of the spectrum, a standing man can absorb most RF energy causing tissue within the body to resonate and generate heat. Therefore, while RF waves are used in modern technology in manufacturing, medical diagnosis and treatment, communications and navigation, there is some danger associated with its use that needs further investigation. The standards generally address RF propagating in free space and set limits for these but there also needs to be consideration for propagation in confined spaces where the waves store and build up their energies after reflecting off of inside surfaces and interfering with each other. The RF in the SAR region of the spectrum is of concern since most of our broadcasting towers operate between these frequencies and are within the public domain which contain confined spaces that may act as waveguides for these wavelengths. This paper focuses on quantifying location characteristics and intensities of RF propagating within empty rectangular structures likened to those of communication waveguide structures, through the proposal of a theoretical model for predicting the locations and intensities of RF hot zones containing RF hot spots. The significance of this work lies in being a tool for RF safety practitioners who can, without the use of cumbersome equipment and necessary skills for measuring RF, use a less expensive and user friendly method for determining the level of RF safety in a confined space by simply knowing its internal dimensions and material of the surfaces; and the RF source characteristics. The work can provide the IEEE standard body with useful information to include in its guidelines.*

Keywords: *RF hazard, SAR, confined space, reflection, waveguide*

1. Introduction

Waveguide technology has managed to constrain microwaves to remain within set boundaries with fixed frequencies that force the waves to behave differently to if they were moving in free space. This technology has offered the ability to efficiently transport energy for communication purposes other than transmission lines. The size of a waveguide may be a few centimetres in width and height and can guide microwaves with wavelengths of the order of centimetres, but what if spaces of larger dimensions are capable of being waveguides and can guide waves of larger wavelengths such as those that correspond to frequencies between 30 to 300 MHz? Such radio-frequency (RF) waves belong to the specific absorption rate (SAR) region of the spectrum where strict exposure limits are set for health and safety protection since a standing man acts as a dipole antenna for this radiation and can absorb maximum energy from propagating RF waves.

This review visits the likelihood for potential energy build-up from RF propagation in rectangular confined spaces that are of waveguide design but with larger dimensions, by investigating the propagation characteristics within these confined spaces. Such confined spaces include silos, tanks, pipes, man-holes, air-condition ducts, tunnels, wells, engine rooms and operator rooms on board vessels. In these confined spaces waves reflect off of the walls and combine constructively or destructively with incident waves producing reinforcement or cancellation respectively. Where there is reinforcement, the intensity of the wave for a particular distance in accordance with the standard may be higher than expected for this distance from the source thereby exposing the worker to larger intensities than the proposed limit.

Standards are not fault proof and may from time to time not fully address all the risks of hazards present since hazards may change depending on their location, intensity, source and presence with other hazards or other perilous conditions and interaction with artefacts. The standards therefore give a probability of safety but do not guarantee it, which should prompt safety practitioners to engage in methods of determination and analysis of the risks posed by hazards in a more inclusive and holistic manner (IEEE, 1999).

2. Literature Review

There has been from time to time, public outcry that electromagnetic waves coming from the various sources cause persons to have headaches, develop rashes, cancer, nervous disorders, irritability, moodiness, breathing difficulties, muscle pain, mental depression, among other claims (Cember, 1996). To address the claims, a compromising position is taken in the IEEE C 95.1 standard with strict limits set at 30 to 300 MHz where the SAR (Rodriguez, 2008). The standards set guidelines generally for RF propagation in free space for plane waves, it is however difficult to accept that RF exposure in open or free space offers the same risk as within a confined space where the energy is confined within boundaries. The standards have not strictly focused on RF propagation in this range, inside of rectangular and cylindrical life-size structures likened to communication waveguides for microwave propagation. According to the Institute of Electrical and Electronics Engineers (IEEE, 1999), a RF hot spot is a highly localised area of relatively more intense radio-frequency radiation that manifests itself in localised areas in which there exists a concentration of radio-frequency fields caused by reflections and/ or narrow beams from antennae. Of special interest to worker safety therefore, is work performed in confined spaces (NCDOL, 2012).

Confined spaces pose potential threats to the health and safety of workers that are not readily visible, (latent hazards), and may lead to fatal injuries because there is failure to recognise and treat the hazard and the suitability of the emergency response (NCDOL, 2012). The OSHA of the United States has set a maximum exposure level of 10 mW/cm^2 for frequencies between 10 MHz and 100 GHz averaged over a 6 minute period, while IEEE sets at 1mW/cm^2 and E (electric) field at 61.4 V/m over the same period.

Given the input of these authorities there seems to be some level of concern and it would be prudent for interested parties to determine in advance the location and intensities of RF as it propagates through a confined space so as to set confined space design parameters and exposure guidelines to protect workers and the public. The literature reveals some of the work done by researchers in the development of propagation models for communication loss through buildings without paying attention to the harmful effects that may accompany this propagation. The models generally introduce free-space propagation without considering restriction of wave movement due to building dimensions. This is justified since most models consider higher frequency or very small RF wavelength for losses in communication networks.

RF from urban communication antennas can reach confined spaces as they bounce off of high rise buildings, reflect off of walls and diffract off the roof tops to the road level (Walfisch and Bertoni, 1988). A study conducted by Iskander et al. (2002) was concerned with the deterioration of communication signals within confined spaces such as buildings and sites due to the multiplicity and complexity of constraints situated inside the building such as walls, furniture, humans, constructive and destructive interference. Therefore, before any planning of implementation of wireless communication there must be thorough understanding of path loss and propagation characteristics.

To predict propagation path we consider three models of interest which have been proposed: i) empirical model which uses a set of equations arranged according to field measurements, ii) site specific (ray tracing) model which uses ray tracing techniques but very computational and difficult to work with and iii) the theoretical model which uses assumed conditions in an ideal setting. Accuracy of ray tracing models depends on trajectory of launching ray, wall parameters, accuracy of locations and knowledge of field orientations which makes the model difficult to work with.

The *shoot and bounce ray* model (SBR) is one of a few ray models for predicting propagation after scatter but has drawbacks in determining whether rays are reflected rays from hitting something or whether the ray came straight or whether have in fact been hit or not and if so, which have been hit. The *ray cone launching* model was constructed to capture the spherical wave-front of the freely propagating wave at the receiving location where an observer will position himself to determine if the receiving point is within the cone. Ray cones are not the answer however since they overlap thereby creating ray doubling errors (Catedera et al., 1998). Interestingly, there have been several methods proposed to mitigate this effect. For instance, Durgin et al. (1997) use the method of distributed wavefront where the contribution of all the rays close to the receiver are taken into account and their sum is the total power received. The distributed wavefronts method is purported to improve the calculated fields but is found to be complex and inherently inaccurate (Porrat and Cox, 2003).

The ray trajectory models are significant but troubling to define so an image method is set to get the trajectory between the receiver and transmitter by placing reflector plates in the path of two transmitters. Lines connecting the receiver to the transmitter and the points of reflection and finally intersection are constructed and used to get the trajectory. A hybrid of image and SBR models are then used to identify the probability trajectory from transmitter to receiver (Tan et al., 1996).

Another propagation model is that of Liang and Bertoni (1998), who assume specular reflection at buildings, diffraction from roofs, building corners where buildings are put into groups of polyhedrons with similar characteristics, reflection coefficients at walls and diffused scattering coefficient. There is much disparity since architecture plays a major role in concrete refinement, windows, and glass, etc. The model identifies additional limitations such as phase of field, position accuracy of building, wall construction, local scattering from street lights, vehicles, people, fading signals. For smaller wavelengths surface roughness is of more concern than for larger waves since there is a tendency for greater diffused reflection.

Erceg et al. (1992) use a line of sight (LOS) model and addresses multiple reflections from walls before reaching the receiver. Attenuation, power of each ray using classical square law with a reflection coefficient that is dependent on the angle between the ray and reflecting surface out of sight (OOS), street. The received power reaching the antenna is then calculated using the square power law, path lengths, reflection coefficient and phase difference between rays reaching receiver.

Despite the advantage stated in the use of ray optics to determine location of waves, it falls short in describing such phenomena as diffraction and interference of waves and under these circumstances, wave optics will have to be used to fully address the wave behaviour. The extent to which interference is a concern for propagating RF is seen inside of smooth metal buildings where ‘radio dead spots’ occur during communication and signals become virtually non-existent.

These dead spots arise because of almost perfect, lossless reflections from smooth metal walls, ceilings or fixtures that interfere with the direct radiated signals. The dead spots exist in 3-dimensional space within the building and motions of only a few inches can move from no signal to full signal. In practice, not only metallic materials cause reflections, but dielectrics (or electrical insulators) also cause reflections. The actual signal levels reflected from insulators depend on a very complicated way on the above characteristics as well as the geometry of the situation.

Suffice it to say, that insulators are not as good at reflecting radio signals as metal surfaces, but even common insulating materials do cause some reflection of radio waves. Multipath occurs when all the radio propagation effects combine in a real world environment. In other words, when multiple signal propagation paths exist, caused by whatever phenomenon, the actual received signal level is the vector sum of all the signals incident from any direction or angle of arrival. Some signals will aid the direct path, while other signals will subtract (or tend to vector cancel) from the direct signal path. The total composite phenomenon is thus called multipath. Two kinds of multipath exist: *specular* multipath -- arising from discrete, coherent reflections from smooth metal surfaces; and *diffuse* multipath -- arising from diffuse scatterers and sources of diffraction (the visible glint of sunlight off a choppy sea is an example of diffuse multipath).

Ray tracing however has been found to be a tedious task for both indoor and outdoor propagation given the obstacles encountered which scatter electromagnetic radiation. Site-specific models have been proposed that give predictions of propagation and scatter from walls and use statistics to predict those from people and chairs etc. Algorithms for model prediction fall into two main categories: ray shooting and method images. The first sets rays in all directions from a transmitter and the second deals with setting each obstacle as a virtual source from which radiation emanates (Porrat and Cox, 1993).

The literature generally takes into account attenuation of RF signals in the communication range of about 900 MHz and above and deals categorically with wall material, obstacle blockage such as machinery and LOS. Measurements on narrow and wide band propagation of RF in buildings have been classified into categories 1-8 describing the environment of propagation such as: residential houses and offices in sub urban, residential and office buildings in urban areas, open factory, open environment such as railway stations, airports and underground such as subways (Molkdar, 1991). The methods all used do not take into account the safety of the individuals in these RF infested areas but rather is concerned with signal losses. There is therefore room for model building that seeks out the propagation characteristics of RF in confined spaces to further improve the safety exposure guidelines for such waves.

3. Research Objectives

The following objectives have been set for RF propagation within confined spaces acting as a transverse electric (TE10) mode waveguide:

a) determination and calculation of hot zone areas using simple trigonometry
b) determination and calculation of hot spot locations and intensities within hot zones using vector analysis and electromagnetic field theory
c) obtaining probability of exposure for single mode and multiple mode operations for TE10 confined spaces

4. Methodology

A waveguide ray tracing model has been proposed in this research that avoids some of the problems encountered in the earlier models that use expanding spherical wave-fronts and measurements. The model proposed has waves confined to one plane making calculations simpler and does not use field measurements which have accompanied uncertainties and errors.

As RF waves propagate down a guide, they reflect off of the walls in a zig zag manner setting up standing waves with the majority of the energy from the electric field travelling down the centre of the space and tailing off at the walls, while the magnetic fields are tangential to the walls.

While energy within the guide does not fall off as rapidly as in open space, there are losses within the guide due to eddy current heating especially at higher frequencies (i.e., smaller wavelengths) where skin depth is present and is comparable to surface roughness. According to Mathew and Stephen (1968), any closed structure such as a pipe or confined space can propagate TE or TM modes. Waveguide transmission becomes more efficient at increasing frequencies which are suitable for microwave communication since the waves are confined and do not expand or diverge in accordance with an inverse square law for RF propagation. (Whitaker, 2002).

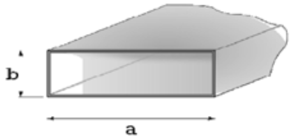


Figure 1. Picture of typical waveguide for communication
Source: http://en.wikipedia.org/wiki/File:Waveguide.svg

An electromagnetic field can propagate along a waveguide in various ways. Two common modes are known as transverse-magnetic (TM) and transverse-electric (TE). In TM mode, the magnetic lines of flux are perpendicular to the axis of the waveguide. In TE mode, the electric lines of flux are perpendicular to the axis of the waveguide (Chatterjee, 1968). At any frequency above the cut-off (the lowest frequency at which the waveguide is large enough), the feed line will work well, although certain operating characteristics vary depending on the number of wavelengths in the cross section (Mathew and Stephenson, 1968).

Waves of frequencies between 20-3,000 MHz are used for line of sight communications in aircrafts, FM, TV and amateur radio broadcasting. Wavelengths at these frequencies are comparable to the dimensions of trees, buildings, hills and as such constitute good reflecting surfaces for setting up constructive and destructive interference between reflected and incident of generated signals. The same is true for propagation of signals between two layers of air at different temperatures (tropospheric ducting) acting as a duct with dimensions that propagate certain modes of transmission. This duct acts as a waveguide for certain frequencies depending on the dimensions and wavelength of the signals (Whitaker, 2002).

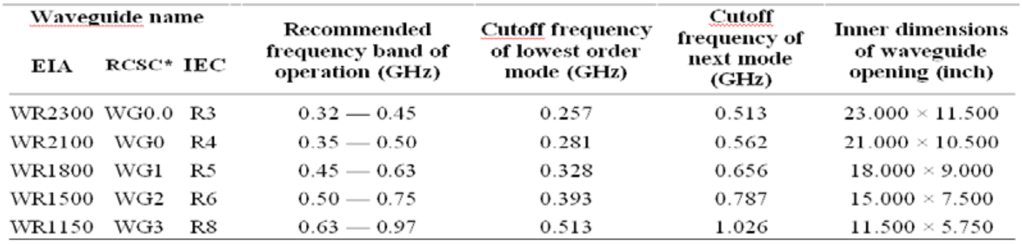
Table 1 shows typical waveguide dimensions for microwaves (Wikipedia, 2014). The last column, column 5, shows the inner dimensions of width and height and it can be observed that the ratio is 2:1. For this condition, propagation of waves can exist without much loss in energy. For such dimensions, there can be a number of possible modes by which energy can be transferred with each being characterised by a distinctive field configuration.

Waveguide propagation can be hypothesised for empty, rectangular spaces of dimensions similar to the wavelength of the propagating RF. For such spaces, there will be a cut-off frequency below which waves will not propagate, all frequencies above may pass. If the guide is however operating in single mode operation, then only one frequency is allowed to pass. According to ECE (2014), the formulae for wave propagation inside a rectangular wave guide are as shown:

1. $c = 3\text{x}10^8$ m/s (c= speed of light in vacuum) (1)
2. $\lambda_{cmn} = 2/\sqrt{[(m/a)^2 + (n/b)^2]}$: (cut-off wavelength for m, n modes for m=1,2,3., n = 0,1,2,3. (2)
3. $\text{Sin}\ \theta = \lambda/\lambda_c = f_c/f$: θ is angle of incidence at entrance of guide (3)
4. $f_{cmn} = c/2\ \{\sqrt{[(m/a)^2 + (n/b)^2]}\}$: cut-off frequency for m, n modes (4)

For any wave propagating down a waveguide, it does so in the Z direction with a group velocity given by U_g. In so doing, a stationary wave pattern is set up as the waves bounce off of the walls of the guide in a 'zig-zag' manner in the XZ plane with velocity in direction of wave travel, U_u, (see Figure 2).

Table 1. Standard sizes of waveguides



Waveguide name			Recommended frequency band of operation (GHz)	Cutoff frequency of lowest order mode (GHz)	Cutoff frequency of next mode (GHz)	Inner dimensions of waveguide opening (inch)
EIA	RCSC*	IEC				
WR2300	WG0.0	R3	0.32 — 0.45	0.257	0.513	23.000 × 11.500
WR2100	WG0	R4	0.35 — 0.50	0.281	0.562	21.000 × 10.500
WR1800	WG1	R5	0.45 — 0.63	0.328	0.656	18.000 × 9.000
WR1500	WG2	R6	0.50 — 0.75	0.393	0.787	15.000 × 7.500
WR1150	WG3	R8	0.63 — 0.97	0.513	1.026	11.500 × 5.750

* - Radio Components Standardisation Committee

There is therefore a component of wave motion in both Z and X directions. The Y-axis addresses the magnitude of the electric field E only in the TE10 mode and there is no component of E in either Z or X directions. The E field spreads across the width of the guide and is half wavelength of the propagating RF for the TE10 mode with maximum field strength at the centre and falls off to zero at the walls. For the TE20 mode, the width is two ½ wavelengths and the E field distribution is E^+ and E^- across the width corresponding to maxima at top and bottom (ECE, 2014).

Should RF waves enter a rectangular confined space at some angle θ to the Z axis (angle of attack), then the entrance would be filled with parallel rays all striking different points on the inside walls of the confined space and reflecting. If the confined space is operating as a waveguide in single mode operation (only one frequency allowed to propagate), then the ray pattern looks like Figure 2, where triangular zones (hot zones) are set up with defined boundaries of propagating and reflected rays from within the guide. Hot spots are found within the confines of the hot zones and occur if the path difference between the reflected and incoming ray is a whole number multiple of the wavelength (i.e., n = 0, 1, 2, 3, 4, etc.). It is not necessarily critical to know exactly where these hot spots are but may be of more importance to know where their probabilities lie within the confined space. This is achieved by first detecting the hot zone locations and the areas of the hot zones.

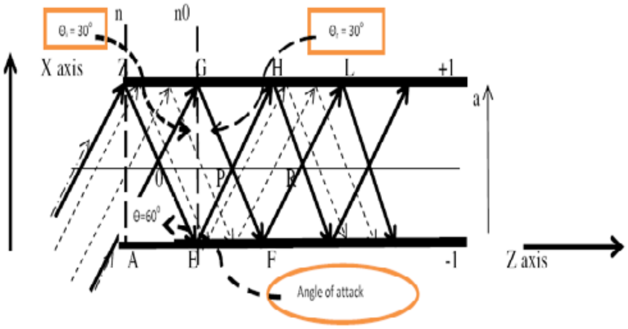


Figure 2. Confined space of width ‘a’, as a single mode operation waveguide for cut-off frequency in TE10

To illustrate this hypothesis let us set up a simple scenario of a propagating RF from an external antenna source for both single and multiple mode operations for a confined space acting as a waveguide. Consider that a rectangular high reflectance air-condition duct of width a = 1.75m and height b = 0.88m is in the line of sight of a RF broadcasting antenna. The incident plane waves propagating some distance from the antenna strike the open rectangular duct (waveguide) at 60 degrees (angle of attack) to the Z-axis of the duct. Determine which frequencies can propagate through this duct and thence the sizes of the hot zone areas so produced if the space is to operate as a waveguide for the TE10 mode in single and multiple modes of operation.

4.1 Single Mode Operation

The cut-off frequency $f_{cmn} = c/2\ \{\sqrt{[(m/a)^2 + (n/b)^2]}\}$; m=1 n=0 for TE10 mode which is 85.7MHz for this guide dimension. For width ‘a’ = 1.75m and angle of incidence 60^o, then $f = f_c / \sin 60$ which is equal to 98.9 MHz. If the antenna emits at 98.9 MHz, then since this frequency is higher than the cut-off, it should be able to propagate down the guide, air-condition duct in this case, once excited. For guide operating as a single mode operation, i.e., for the TE10 mode only, waves with frequency 98.9 MHz that strike the entrance at 60^o will propagate and fill up between the points A and Z. Incident waves strike the wall of the duct at Z and G and at 30^o to the normal (n0) at the wall’s surface and reflect at the same angle 30^o and continue to E and F. These will then reflect from this surface to strike the first surface at H and L (see Figure 2).

Interference occurs within triangles: OZG, PEF and RHL where incident and reflected rays cross. These are considered areas of potential RF hot spots. The hot zones are all of same area and repeat periodically and give the probability of RF hot spot accumulation, where the waves interfere constructively. These hot spots will have higher field intensities than the waves that do not interfere constructively and are therefore potential points of higher exposure.

4.2 Multiple Mode Operation

For the fixed waveguide width, a = 1.75m, the cut-off frequency is 85.7 MHz for the dominant TE10 mode. Varying frequencies of RF can propagate outside the single mode operation but their angles of attack will be different. Theoretically, using geometric construction or ray tracing technique, the smaller the angle then the larger the hot zone area as seen in Table 2 and Figure 3.

We can infer that the probability or likelihood of finding hot spots decreases with increasing angle of attack, i.e. the areas get smaller and smaller so interference patterns decrease. Based on this it should also be noted that the allowed propagating frequency decreases with increasing angle of attack (see Figure 4).

Figure 5 shows that as the guide width increases the cut-off frequency decreases, broadcasting frequencies are expected to be between the 50 and 150 MHz frequency band generally. Confined spaces with dimensions corresponding to values between 1m and 3m in width may therefore be waveguides in the TE10 mode for these signals.

One deliverable so far based on our discussions is the construction of a SAR structural guide chart that predicts whether there is potential threat to RF exposure within a structure from a nearby source (see Figure 6). This of course is for the TE10 mode and can be extended to other modes as well as multiple mode operations and can be useful in building design drawings.

Table 2. Zone area and propagating frequency (f_c= 85.7MHz) for varying angles of θ.

θ/ º	Tan θ	Area of zone A = .7656/ tan θ	Frequency MHz (f = f_c/ sin θ)	Sin θ
2	0.35	21.87	2857	.03
3	.052	14.72	1714	.05
4	.070	10.94	1224	.07
5	.0875	8.75	952	.09
6	0.105	7.29	779	.11
7	.123	6.22	714	.12
8	.141	5.43	612	.14
10	.176	4.35	504	.17
20	.36	2.13	252	.34
30	.58	1.32	171.4	.5
35	.70	1.09	150.3	.57
50	1.19	.649	112.3	.77
60	1.73	.443	98.5	.87
70	2.75	.279	91.1	.94
75	3.73	.205	88.3	.97
80	5.67	.13	87.0	.985
85	11.40	.067	86.0	.996
86	14.3	.054	85.957	.997
87	19.08	.04	85.786	.999
88	28.6	.027	85.7857	.999
89	57.3	.013	85.717	.9998

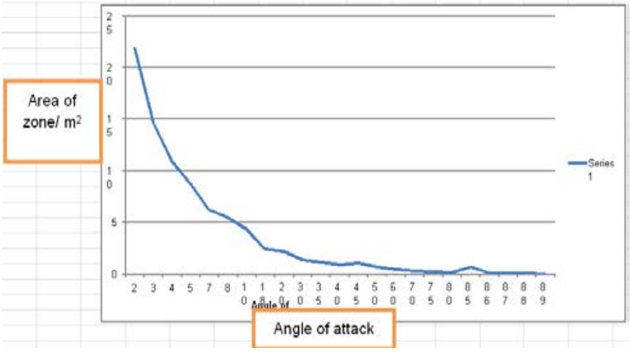


Figure 3. Graph of hot zone area versus angle of attack, θ

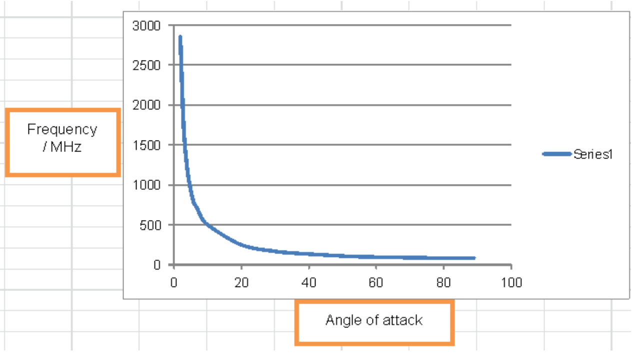


Figure 4. Graph of propagating frequency versus angle of attack, θ

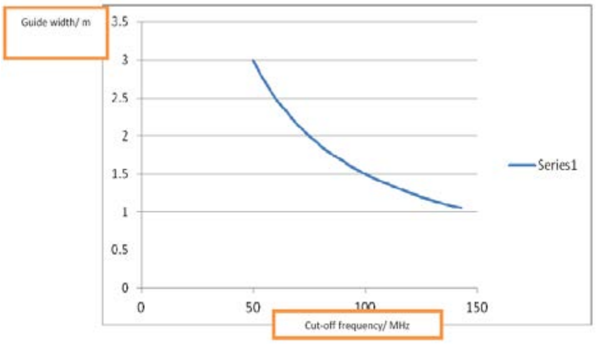


Figure 5. Graph of guide width versus cut-off frequency

Figure 6. SAR structural guide chart (Cut-off frequencies in TE10 mode for varying rectangular confined space widths ‘a’ in Single Mode Operation).

Confined space name	a/ m	b/ m	f_c/ MHz: $f_{cmn} = c/2 \{\sqrt{[(m/a)^2 + (n/b)^2]}$	Single mode freq. at 60^0 /MHz	SAR
CS300	3.00	1.50	50.0	57.7	Yes
CS275	2.75	1.35	54.5	62.9	Yes
CS250	2.50	1.25	60	69.3	Yes
CS225	2.25	1.12	66.8	77.1	Yes
CS200	2.00	1.10	75	86.6	Yes
CS175	1.75	1.40	85.7	98.9	Yes
CS150	1.50	0.75	100	115.5	Yes
CS125	1.25	0.65	120	138.5	Yes
CS110	1.10	0.55	136	157.0	Yes

5. Calculation and Analysis

5.1 Hot Zone Areas

The area of a hot zone is given by $a^2/4 \tan \theta$, where θ is the angle of attack of the incoming waves to the xz plane of the space and ‘a’ is the width of the space. As θ decreases the zone area increases up to the guide length otherwise the hot zone area within the guide begins to decrease. In this regard, the effective area of the hot zones found for a given width within the guide is therefore restricted by the length of the guide and defined for: $\theta < \tan^{-1} a/l$, where l is the length of the guide.

$A = ½ (a/2)l$, $\tan \theta = a/2 /l/2 = a/l$

Therefore, $l = a/ \tan \theta$, and $A = a^2/ 4\tan \theta$

The maximum area A_O of the hot zones is therefore $a^2/4 \tan^{-1}a/l$. So for a guide of width 1.75m as pointed out in our scenarios earlier, with a guide length of say, 4m, the minimum angle for optimal area is 23.6 degrees and the max hot zone area is therefore $A_0 = a^2/ 4 \tan 23.6 = 1.76m^2$. Larger angles of attack will see smaller frequencies, as long as above the cut-off frequency, propagate and hence smaller and less zone areas which means smaller probabilities of exposure. Figure 7 shows smaller angle giving smaller area inside guide.

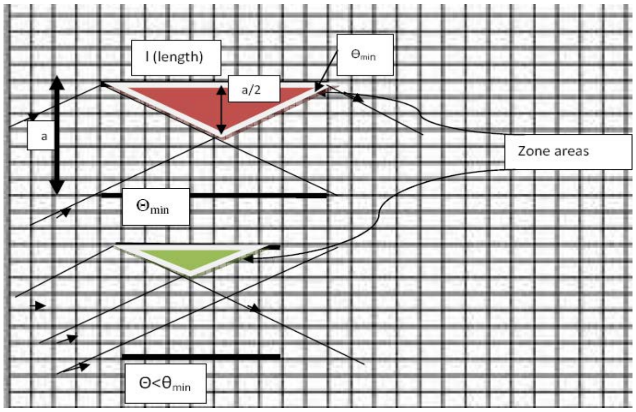


Figure 7. Grid with zone areas

5.2 Hot Spot Location

The hot spot locations are identified by tracing any two rays from their origin at the entrance of the guide to their point of intersection and if the path difference Δ between them is a whole number of wavelengths, nλ, then we have constructive interference and a hot spot. We first divide the guide space into a grid of equal squares. Using vector analysis, vector r3 is the resultant of vectors r1 and r2 (see Figure 8). Note that (r4 – r3) is the path difference Δ, which is the vector along the entrance width. From Figure 8, r3 = 8i+j and r4 = 8i+9j, so r4 – r3 = 8j from which the magnitude Δ becomes 8 units as seen on the grid.

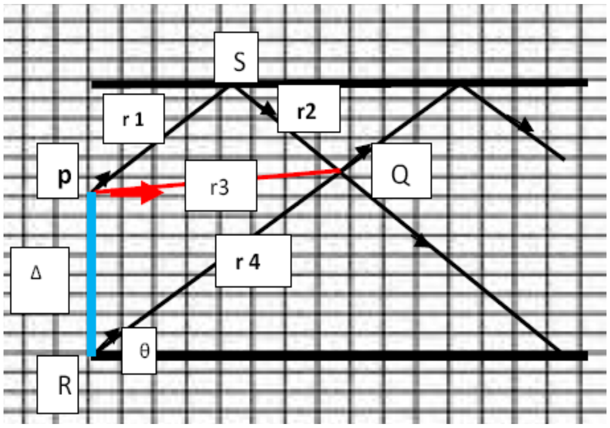


Figure 8. Vector analysis for guide hot spots

For example, from earlier guide width 'a' = 1.75m, which is divided into 14 units on the grid so each unit = 1.75/ 14 = 0.125m, which implies that 1m = 8 units. See Table 2 for f = 98.5 MHz which gives $\lambda = c/f = 3\text{x}10^8/98.5\text{x}10^6 = 3.1$m, for angle of attack of 60 degrees. Is the point Q a hot spot for the two rays leaving the guide entrance? We must equate this to nλ, where λ=3.1m. As we see; n =1/3.1 < 1,2,3 i.e., whole numbers so this is not a hot spot. If we allow for a higher frequency and hence larger area by making the angle of attack lower, then say for angle 30 degrees, frequency = 171.4MHz and λ= 1.75m (see Table 2). This implies that n = 1 so we have a hot spot for the lower angle and wider area. There is a potential hot spot then in the guide provided that the length is long enough to accommodate the zone area. We can therefore set up a table for the TE10 guide for different frequencies above the cut-off of 85.7 MHz and see what path differences and frequencies would lead to hot spots.

Our earlier notion of the number of hot spots increasing as the frequency increases or as θ decreases has been verified theoretically. This does not discount that there may already be an existing threat by its normal presence. For this guide then, there is greater probability of higher exposure at 952 MHz (5 hot spots) than there is for 504 MHz (3 hot spots) and similarly for 171.1 MHz (1 hot spot).

Table. 3. The number of hot spots with increasing frequency

Frequency, f/ MHz	λ/m	θ/ degrees	Δ/ m	n	Frequency, f/ MHz
98.5	3.1	60	1	<1	no
171.4	1.75	30	1.75	1	yes
504	0.59	10	0.59	1	yes
504	0.59	10	1.75	3	yes
504	0.59	10	1.18	2	yes
952	0.315	5	0.315	1	yes
952	0.315	5	1.575	5	yes
952	0.315	5	0.63	2	yes
952	0.315	5	0.945	3	yes
952	0.315	5	1.26	4	yes

5.3 Hot Spot Intensities

Earlier we obtained a path difference between a resultant ray and incident ray, r3 and r4 respectively which set the stage for determining whether a hot spot was present or not. Once a hot spot is found to be present, we must now calculate the net intensity of the superimposed waves at the point. Accompanying the path difference is a phase difference of 2πΔ/λ, which has been left out here but could be easily placed in the reflected wave as ${}_rE = {}_rE_0\, e^{j(\omega t - [\beta + 2\pi\Delta/\lambda]z)} \cdot \mathbf{a_x}$

The field intensity of the incoming vertically polarised wave is $E_i = E_0\, e^{j\omega t} \cdot e^{-\gamma z}$, (unbounded) where $\gamma = \alpha + j\beta$ and γ is imaginary if (attenuation factor) α = 0. i.e. there is no attenuation of the wave. Inside the confined space, ${}_iE = {}_iE_0\, e^{j(\omega t - \beta z)} \cdot \mathbf{a_x}$ and ${}_rE = {}_rE_0\, e^{j(\omega t - \beta z)} \cdot \mathbf{a_x}$, the sum of the two rays arriving at Q:

$$E(z,t) = {}_iE + {}_rE = {}_iE_0\, e^{j(\omega t - \beta z)} \cdot \mathbf{a_x} + {}_rE_0\, e^{j(\omega t - \beta z)} \cdot \mathbf{a_x}. \quad (1)$$

Both E field intensities still travelling in the forward 'z' direction.

Equation (1) gives the time varying E field in the z direction and the stationary wave set up in the x direction, where ω is the frequency, β is the phase constant of the waves and $\mathbf{a_x}$ is the unit vector in the x direction. The waves are vertically polarized with no change upon reflection.

Fresnel relationship for waves striking a boundary with E field normal to the plane of incidence (xz plane) and parallel to the boundary (zy plane):

$${}_rE_o/\,{}_iE_o = [\theta_i \cos \theta_t - \theta_t \cos \theta_t]/\,[\theta_i \cos \theta_i + \theta_t \cos \theta_t]. \qquad (2)$$

where θ_i and θ_t are the intrinsic impedances of medium 1 and medium 2 which could be air and aluminium respectively and are calculated from: $\theta = \sqrt{(\mu\omega/\sigma)}$ and θ_i and θ_t are the angles of incidence and transmission of the ray striking the boundary interface (Hecht, 1975).

Assuming perfect reflection and no transmission through the boundary, then $\theta_t = 0$, and eqn 2 becomes:

$${}_rE_o/\,{}_iE_o = [\theta_i \cos \theta_i - \theta_t]/\,[\theta_i \cos \theta_i + \theta_t] \qquad (3)$$

Therefore, ${}_rE_o = [\theta_i \cos \theta_i - \theta_t]/\,[\theta_i \cos \theta_i + \theta_t]\,.\,{}_iE_o$ which can be written as:

$${}_rE_o = \theta\,{}_iE_o \qquad (4)$$

Equation (1) becomes:

$$E(z,t) = = {}_iE_0\, e^{j(\omega t - \beta z)}\, \mathbf{a_x} + \theta\ {}_iE_0\, e^{j(\omega t - \beta z)}\, .\, \mathbf{a_x}. \qquad (5)$$

So, $E(z,t) = {}_iE_0\, e^{j(\omega t - \beta z)}\,(1 + \theta)\, \mathbf{.\ a_x}$ (6)

This can be further written as:

$$E(z,t) = {}_iE_0\, e^{j(\omega t - \beta z)}\,(1 + \theta)\ \mathrm{Sin}\ k_x x. \qquad (7)$$

which gives the travelling part of the electric field and the stationary part of the standing wave which essentially is the electric field intensity of the constructive wave at the point Q. this can be further simplified using the imaginary part of (7) to get

$$E(z,t) = {}_iE_0\ \mathrm{Sin}\ (\omega t - \beta z)\ .\ (1 + \theta)\ \mathrm{Sin}\ k_x x \qquad (8)$$

6. Results

From above, for a hot spot with path difference, $\Delta = x$ due to two intersecting waves, the electric field at some point Q say, within the hot zone of these intersecting waves is given by (9)

$$E(z,t) = {}_iE_0\ \mathrm{Sin}\ (\omega t - \beta z)\ .\ (1 + \theta)\ \mathrm{Sin}\ k_x \Delta \qquad (9)$$

The paper does not specifically deal with diffraction effects at the entrance of the guide, some diffused diffraction at the surfaces, phase change at Q and that the guide will not be a perfect conductor. There was also the assumption that there would be total reflection and no transmission or very little at the boundary interface.

7. Conclusion

This article presents a thought provoking notion of large waves in SAR region propagating down rectangular confined spaces just as microwaves would in waveguides setting up standing waves due to interference of incident and reflected waves within the space. These RF hot spots possess the potential to contain higher field intensities than if the waves were propagating in free space. When we therefore investigate safety hazards due to noise, lighting, toxic and gas build-up within confined spaces, accumulation of RF along the confined space must also be studied.

While the discussion is purely speculative and requires experiment for validation, it seems justifiable theoretically, that RF hot zones can exist in confined spaces. The determination of these RF hot zones can be of importance in setting building code guidelines for construction of antennae and RF towers close to communities. The work presented here is limited in that only rectangular, high reflective, empty confined spaces have been brought to the fore. Confined spaces are expected to be used by people and contain artefacts such as furniture, tools, etc which makes a very complex situation of multiple reflections and diffraction effects. The intention however was to deliver the trivial case and then extend to the more complex.

Moreover, other modes of operation (such as TE11, TE21, and TE31) were not discussed since the dominant mode was thought to be sufficient and does not infer that the other modes are less important. It is hoped that with experimental work and further research that the contribution offered here would find resting place in RF safety guidelines and RF propagation hot zone management in confined spaces.

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Authors' Biographical Notes:

Ricardo Rodriguez *is currently pursuing a PhD degree in Mechanical Engineering under the supervision of Professor Winston Lewis. His research concerns itself with the modeling of RF in confined spaces. Mr. Rodriguez holds a BSc degree in Pure and Applied Physics, MSc in Engineering Management and MPhil in Mechanical Engineering from The University of the West Indies. He was also awarded a special prize for his contribution on Opportunities Management at the Prime Minister's Award Function, 2004 in the Bright Solutions category. He has worked at the Trinidad and Tobago Bureau as a Standards Officer III where he developed standards on gasoline, diesel and Health and Safety Standards in support of the Occupational Safety and Health Act. Mr. Rodriguez was also the Co-Chair with a Telecommunications Authority of Trinidad and Tobago representative on a committee mandated to review the local radiation exposure guidelines for Trinidad and Tobago.*

Winston G. Lewis *is presently Professor of Industrial Systems Engineering of the Faculty of Engineering at The University of the West Indies. He is a registered professional engineer and Fellow of the Association of Professional Engineers of Trinidad and Tobago (APETT), and a member of the Order of International Fellows in the Association for Iron and Steel Technology and the American Society of Mechanical Engineers (ASME). He was a member of the steering committee appointed for the establishment of The University of Trinidad and Tobago (UTT), and Chairman for the development of national standards on workplace design at the Trinidad and Tobago Bureau of Standards. Professor Lewis' research and development work is in metallurgical and Industrial engineering, sheet metal forming, manufacture of the steel-pan musical instrument, applied ergonomics and workplace design, engineering quality management and nano-technology. He has authored 77 academic papers with 39 Journals and 38 Conference Papers and has successfully supervised one PhD candidate, three MPhil, and forty-four graduate students with their MSc, final year projects.*

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