SAFETY CRITERION FOR MULTI-SOURCE WIRELESS USAGE IN VARIOUS REFLECTIVE ENVIRONMENTS

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INTRODUCTION

It should be possible to use wireless informatics to reduce healthcare costs, while improving patient care by reducing medical errors and increasing the efficiency and speed of healthcare delivery. However, this would require safe operation of multiple wireless sources near medical devices within hospital environments with walls of various reflectivities. Electromagnetic interference (EMI) with medical devices can be avoided if wireless sources are operated at an appropriate *minimum separation* from medical devices. However, no currently-recommended minimum separations are valid in substantially reflective environments, or in the presence of **multiple** sources. This paper proposes a suitable separation criterion.

In order to control EMI risk within hospitals, *ad-hoc* testing has been recommended [1]. The test estimates a *minimum separation* between a specific radio-frequency (RF) source and a particular medical device. *Ad-hoc* testing should take place in a large (e.g., 9x9 meter) open area, that is, in an "*ad-hoc* lab" set aside for this purpose. However, it is unknown whether minimum separations determined in the *ad-hoc* lab are applicable in an *in-situ* hospital room, because the reflectivity of the *in-situ* environment may be different from that of the lab. Also, it is unknown whether the estimated minimum separations are applicable *in-situ* when multiple wireless sources are present.

INDOOR FIELDS

The **direct field** E_D radiated by an RF source of directivity D radiating P watts in free space at separation *r* is given by

$$E_D(r) = \sqrt{\frac{\eta D P}{4\pi r^2}} \ \text{V/m RMS}$$

where η is the intrinsic impedance of free space. When an RF source radiates in a hospital room, the ***total field*** E_T at any location is made up of the ***direct field*** E_D plus the ***indirect field*** E_I reflected from the room's walls, floor and ceiling

$$E_T = E_D + E_I .$$

The **volume average of the indirect field** can be estimated as [2]

$$\tilde{E}_I = \sqrt{\frac{4\eta P}{A_{in}}} .$$

where the indirect absorption of the room is

$$A_{in} = \frac{AS}{S - A} ,$$

and the total area of the surfaces of the room is S. The room absorption is

$$A = \sum S_i \tilde{\alpha}_i$$

where S_i is the area of patch $\# i$ of surface and $\tilde{\alpha}_i$ is the angle-averaged power absorption of the patch, given by

$$\tilde{\alpha} = 2 \int_0^{\pi/2} \left[1 - \frac{1}{2}\left(\left|\Gamma_\parallel\right|^2 + \left|\Gamma_\perp\right|^2 \right) \right] \sin\theta \cos\theta d\theta ,$$

$\Gamma_\parallel$ and $\Gamma_\perp$ are the reflection coefficients for the parallel and the perpendicular polarizations, and θ is the angle of incidence from the normal [3]. For example, at 2.4-GHz, walls made of 5-cm brick, 42-cm concrete, 4.5-cm wood, and 1-mm glass have absorption coefficients, $\tilde{\alpha}$, of 0.65, 0.79, 0.90 and 0.99 respectively.

If the walls of the room are highly absorptive so that $\tilde{\alpha}_i \to 1$, the absorption coefficient A becomes approximately equal to the total surface area S, and the indirect absorption $A_{in} \to \infty$. Then the indirect field approaches zero and the direct is the only contribution to the field in the room. Conversely, if the walls are highly reflective, $\tilde{\alpha}_i \to 0$, and $A \to 0$, then $A_{in} \to 0$ and the indirect field becomes large.

If the room contains multiple sources with a total radiated power of P_T, then the indirect field is

$$\tilde{E}_I = \sqrt{\frac{4\eta P_T}{A_{in}}} .$$

This formula is a useful guide to minimum separations, as discussed in the following.

MINIMUM-SEPARATION SAFETY CRITERION ONLY WORK WITHIN A TRANSITION DISTANCE

Figure 1 shows the electric field strength at a 1.6 m height in a 6.5-by-6.6 m room, due to a vertical half-wave dipole near the center of the room, radiating 100 mW. Close to the source, the direct field is much larger than the indirect field so the total field strength declines with distance from the source. Far from the source, the direct field strength can be much smaller than the volume average of the indirect field. The actual field strength in Fig. 1 exhibits a standing-wave pattern with many local minima and maxima over most of the area of the room.

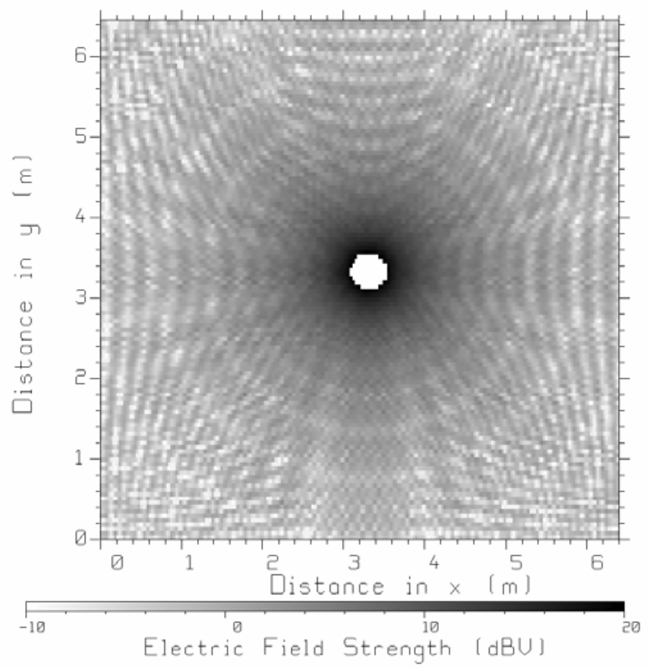

Figure 1: The electric field strength in a 6.5 by 6.6 m room due to a dipole radiating 100 mW near the center of the room.

Minimum separations usefully manage the risk of EMI only when field strength declines with distance from the source. In the region where the standing waves are the dominant behaviour, no minimum separation can be specified. When moving away from the source, the direct field declines until it equals the indirect field. This **transition distance**, r_m, is given by

$$r_m = \sqrt{\frac{DA_{in}}{16\pi}}\ \sqrt{\frac{P}{P_T}}$$

where P is the power radiated by the source, and P_T is the total power radiated by all of the sources in the room. If this transition distance is very close to the source, minimum separations will not be a useful strategy for managing EMI.

Table 1 illustrates the transition distance r_m for rooms of various absorptions, with various number of sources. Consider a 125-mW cell phone operating at 2.45 GHz in an environment where there may be several wireless-local-area-network access points (APs), each radiating 100 mW. Suppose the room dimensions are 4.1 m by 2.9 m, with ceiling height 2.3 m. In Table 1, all the surfaces of the room have the same reflection coefficient, except for a 0.75-by-2.3-m doorway having zero reflection. The purpose of the table is to demonstrate the relationship between wall absorption, the number of RF sources, and the distance r_m to the indirect field.

Table 1

Transition distances r_m where direct and indirect fields are equal for various absorption coefficients.

		RF sources					
$\tilde{\alpha}$	**example**	**cell phone alone**		**cell phone plus one AP**		**cell phone plus five APs**	
		$\tilde{E}_I$ V/m	r_m m	$\tilde{E}_I$ V/m	r_m m	$\tilde{E}_I$ V/m	r_m m
0.2	metallic	3.8	0.7	5.1	0.4	8.4	0.3
0.4		2.3	1.1	3.1	0.7	5.2	0.5
0.6		1.8	1.6	2.1	1.1	3.5	0.7
0.7	5-cm brick	1.3	2.0	1.7	1.5	2.8	0.9
0.8	42-cm concrete	1.0	2.5	1.3	1.7	2.2	1.1

In a hospital, medical staff might be told to maintain a separation of “arm’s length” or about 1 m from medical devices. There will be no interference provided that the field strength farther than 1m from RF sources is less than the medical device’s immunity, of for example 10 V/m. When the averaged indirect field strength is more than half of the device’s immunity, standing-wave maxima can lead to fields in excess of immunity. Thus, in Table 1, when room reflection is high, a cell phone and one access point give rise to an indirect field of 5.1 V/m, and the corresponding value of r_m is only 0.4 m, less than “arm’s length”. Conversely, in highly-absorptive rooms, a cell phone and five APs lead to an indirect field of only 2.2 V/m and r_m is 1.1 m, about equal to arm’s length. Thus, r_m is a good indicator of when minimum separations are useful for ensuring EMC.

CHARACTERIZING A ROOM’S INDIRECT FIELD

To characterize a room’s indirect field, the room’s absorption, A , must be found. The field strength along a straight-line path in the room, starting near the source and moving away from it, should allow the value of the indirect field to be found, permitting the room absorption to be estimated. For example, consider a path in the room of Fig. 1 starting 30 cm from the source and moving toward the upper right-hand corner of the room. The field strength as a function of distance from the source is shown in Fig. 2. The field strength declines as the inverse of distance close to the source (circles), and then becomes a standing-wave pattern at larger distances (solid line). Close to the source, three points at distances of $r_1 = 30$, $r_2 = 60$ and $r_3 = 90$ cm can be used to characterize the direct field,

$$E(r) = \frac{E_0}{r} .$$

This is done by minimizing the error between the three data points $\{r_k, E_k : k = 1,3\}$ and $E(r)$, by calculating E_0 using

$$20 \log E_0 = \frac{1}{3}\left(\sum_{k=1}^{3} \left(20 \log E_k + 20 \log r_k \right) \right).$$

Next, the decline in field strength with distance can be modeled by combining the direct field and the indirect field on an energy basis to obtain

$$E(r) = \sqrt{\left(\frac{E_0^2}{r^2} \right) + \tilde{E}_I^2} ,$$

where E_0 is known, but the value of the indirect field $\tilde{E}_I$ is unknown. $\tilde{E}_I$ can be found by minimizing the error between $E(r)$ and the standing-wave pattern, graphed as a solid line in Fig. 2. If the data points of the solid line in Fig. 2 are $\{r_k, E_k : k = 1, N\}$, then $\tilde{E}_I$ is chosen to minimize

$$err\left(\tilde{E}_I\right) = \sum_{k=1}^{N} \left(E_k - \sqrt{\left(\left(\frac{E_0}{r_k} \right)^2 + \left(\tilde{E}_I \right)^2 \right)} \right)^2 .$$

The value of $\tilde{E}_I$ which minimizes the error is readily found by trial and error.

Simulations were used to validate this process. Ray-tracing simulations estimated the fields in Fig. 1. Since the simulation used a known absorption, the validity of the procedure outlined above to estimate this absorption could be confirmed. Thus for the 6.5-by-6.6 m room of Fig. 1, the surface area of the room was 146.3 m^2 and the room absorption was $A = 110$ m^2. Using the three points close to the antenna, E_0 was found to be 2.17 V/m, which was very close to the true value of 2.22 V/m. Then using points lying from 1 m to about 4.2 m from the source, sampled at a 0.5-cm interval, the standing wave pattern was characterized. $\tilde{E}_I$ was found to be 0.338 V/m, also very close to the true value of 0.340.

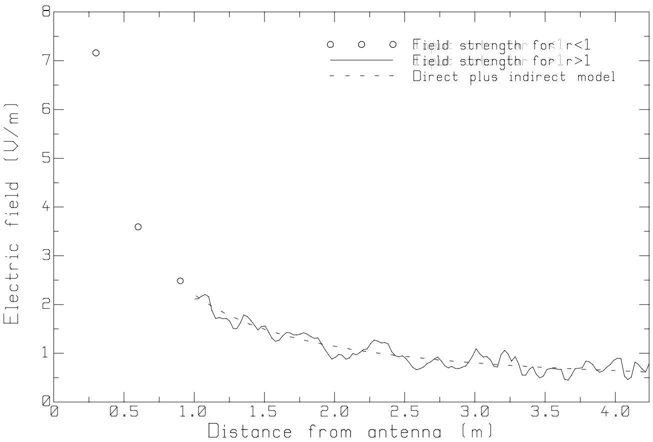

Figure 2: Field strength along a path from the source to the upper right corner in the room of Fig. 1.

To calculate the room absorption from $\tilde{E}_I$, the indirect absorption was evaluated using

$$A_{in} = \frac{16\pi}{D} \frac{E_0^2}{\tilde{E}_I^2}$$

and then the room absorption was given by

$$A = \frac{A_{in} S_T}{\left(S_T + A_{in} \right)} .$$

Thus using $\tilde{E}_I =$ 0.338 V/m, it was found that $A_{in} = 1263$ m^2 and $A = 131$ m^2. Thus the estimated absorption was within about 20% of the true value of 110 m^2. Note that this 20% error had a relatively small effect on changes in minimum separations as discussed below.

In practise, measurements must be made to characterize either an *ad-hoc* testing lab or a hospital room. This can be done by using a measurement system to obtain field strength as a function of distance from an RF source at many closely-spaced points. A robot system such as that described in [4] can be used. A transmit dipole can be located on a tripod approximately at the center of the room. The robot can carry a receive dipole connected to a spectrum analyser, and measure the field strength every 0.5 cm along a straight-line path, starting about 30 cm from the dipole, and moving towards one corner of the room. Then, the data set can be analyzed by the methods given above to determine the room absorption, as was done using simulated data.

AD-HOC AND *IN-SITU* SCENARIOS

Suppose *ad-hoc* testing is done with a given RF source and medical device to determine that the required minimum separation, r_{adhoc} , is 70 cm. Suppose also that *ad-hoc* testing is done in a lab of known absorption, A_{adhoc}. Can the minimum separation estimated in the lab, r_{adhoc} , be transferred to an *in-situ* hospital room with a different absorption A_{insitu} ? Using the direct-field-plus-indirect-field model outlined above, the minimum separation, r_{insitu} , required in the hospital room is given by

$$r_{insitu} = \frac{1}{\dfrac{1}{r_{adhoc}} + 4\sqrt{\dfrac{\pi}{D}}\left(\dfrac{1}{\sqrt{A_{in,adhoc}}} - \dfrac{1}{\sqrt{A_{in,insitu}}}\sqrt{\dfrac{P_T}{P}}\right)},$$

where $A_{in,adhoc}$ and $A_{in,insitu}$ are the indirect room absorptions for the *ad-hoc* lab and hospital room respectively. In *ad-hoc* testing there is only one source of power P. But in the *in-situ* environment, there may be many sources of total power P_T contributing to the indirect field. The above formula gives the minimum separation from one source, assuming that the other sources are far enough away.

Ad-hoc testing is best done in a highly-absorptive lab because the direct field of the RF source is wanted. Suppose the lab absorption is $A_{in,adhoc} = 125$ m^2 and a minimum separation of 70 cm is found. Suppose the *in-situ* location has an absorption of $A_{in,situ} = 110$ m^2 and the room surface area is $S =$ 146.3 m^2. The corresponding indirect absorptions are $A_{in,adhoc} =$ 859 and $A_{in,insitu} = 443$ m^2. With $r_{adhoc} = 70$ cm, and assuming that there is only one source present so $P_T = P$, and assuming that $D = 1.64$ for a half-wave dipole source, the *in-situ* separation is $r_{insitu} = 70.78 \approx 70$ cm. Thus, the lab and *in-situ* rooms are not much different so the value found by *ad-hoc* testing would be similar to the one that should be used in the hospital room. Suppose that it is known that the RF source radiates $P = 125$ mW, and that there are five APs, each radiating 100 mW. Then with $P_T =$ 625 mW, it is found that $r_{insitu} =$ 97 cm. Thus, a considerably larger minimum separation is required because the power radiated by the APs raises the value of the indirect field. As a result, an additional separation is required to account for the higher indirect field.

CONCLUSION

Minimal separations can be used to manage the risk of interference within hospital rooms as long as the indirect field is low enough that total field strength decreases with distance from the source for a range of distances comparable to the minimum separation.

To characterize a room, the room absorption must be measured. This paper outlines a method which measures the field strength along a radial path away from a source, and then deduces the value of the indirect field and hence the room absorption.

Ad-hoc testing should be done in a laboratory with relatively high room absorption in order to determine the minimum separation between a specific RF source and a medical device. The hospital-room environment or *in-situ* environment where the source and medical device will be in day-to-day use may have a different absorption from the lab. Also, there may be other RF sources present in the *in-situ* case which may increase indirect fields. A formula has been presented for transferring the minimum separation estimated in the *ad-hoc* lab to the *in-situ* hospital room environment, accounting for the difference in the room absorption and for the presence of other RF sources.

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