8. Mutual Interference of Part 15 Devices

7.1. Direct Sequence Spread Spectrum Devices

7.1.1. Outdoor Devices

In "Interference Analysis of Part 15 Devices and LMS Wideband Systems - Initial Calculations", Section 8 it was noted that the typical direct sequence spread spectrum Part 15 device has a NFR of 1. It is useful to calculate the number of these devices which could co-exist with similar devices. If this figure of NFR = 1 were used in the same calculation as before, in order to estimate the number of co-existing systems that could exist in the same band, the results are as given in Table 8.

Table 8 Number of 1W outdoor Part 15 devices for 10% probability of blocking.

Ft=	0.01	0.1	0.25	0.5	0.75	1
NFR=	1	. 1	1	1	1	1
N=	22	2.3	0.9	0.45	0.3	0.25

Assuming that the effective unwanted transmitted power, is 20 dBm, due to the use of directional antennas, then the NFR increases to 1.77. Table 9 then results.

Table 9 Number of outdoor Part 15.247 devices for 10% probability of blocking.

Ft=	0.01	0.1	0.25	0.5	0.75	1
NFR=	1.77	1.77	1.77	1.77	1.77	1.77
N=	70	7	2.8	1.4	0.9	0.7

Tables 8 and 9 correspond to the number of co-existing direct sequence Part 15.247 systems within the unit area, which is the propagation distance. This propagation distance will be less than that of the LMS site due to the 30 ft antenna height and the lower processing gain (assuming that the LMS system has a 10 dB desensitization factor).

The relative signal strength will be in the order of

$$10\log(10)+20\log\left(\frac{200\times 6}{30\times 30}\right)=12.5dB$$

The relative distance is therefore, in the case of pole mounted devices,

$$d_1/d_2 = 10^{12.5/40} = 2.05$$

Thus, to relate Table 9 to correspond to the previous Tables, the number of co-existing pole mounted devices, in the unit area can be quadrupled. In comparison with Table 4, it is clear that for direct sequence pole mounted outdoor Part 15.247 devices, the limit to the number that can be deployed is NOT the interference to LMS. About twice as many Part 15 devices can be tolerated by the LMS system that can co-exist with other Part 15 devices.

7.2. Frequency Hopping Devices

Let us now consider Part 15 frequency hopping systems. If there are N systems with M channels, then the probability that the signal is blocked is derived in Annex A.

$$P_{bFH} = \sum_{n=0}^{N}\left(1-\left(1-\frac{1}{2(NFR)^2}\right)^n\right)\left(1-\left(1-\frac{1}{M}\right)^n\right)\frac{(NF_t)^n}{n!}e^{-NF_t}$$

Assuming that the device requires a 12 dB signal to noise receive ratio, then the effective NFR is 0.5 for co-channel interference. As before, it is assumed that the effective interfering transmitted power is 20 dBm to account for the use of directional antennas, and hence the NFR is taken as unity.

The minimum frequency channel is 25 kHz and thus 1023 hopping channels would occupy 25.575 MHz. Thus the maximum number of hopping channels that can be contained within the ISM band is 1023.

If 1% of the channels are blocked then this represents an over-the-air bit error rate (BER) of about 1 in 10^2. The acceptance[6] of this degree of BER is not known, but it is usual to design radio data links, at these frequencies, for over-the-air BER of about 1 in 10^3.

Tables 10, 11, and 12 show the number of co-existing frequency hopping systems, for 10% and 1% blocked channels, for code lengths of 1023, 511 and 255.

[6]Some frequency hopping radios avoid the use of blocked channels, and the effect of this can improve the effective BER. The speed of the hopping and other parameters will effect this.

Table 10	Number of 1W outdoor Part 15 FH devices For 1% probability of blocking M =1023					
Ft=	0.01	0.1	0.25	0.5	0.75	1
NFR=	1	1	1	1	1	1
M=	1023	1023	1023	1023	1023	1023
N=	1050	105	42	21	14	11

Table 11	Number of 1W outdoor Part 15 FH devices For 1% probability of blocking M =511					
Ft=	0.01	0.1	0.25	0.5	0.75	1
NFR=	1	1	1	1	1	1
M=	511	511	511	511	511	511
N=	520	52	21	10	7	5

Table 12	Number of 1W outdoor Part 15 FH devices For 1% probability of blocking M =255					
Ft=	0.01	0.1	0.25	0.5	0.75	1
NFR=	1	1	1	1	1	1
M=	255	255	255	255	255	255
N=	260	26	11	5.2	3.4	2.6

As for the direct sequence devices, the unit area is about half that of the LMS unit area, and hence, in order to compare, the numbers given in Tables 10, 11 and 12, can be quadrupled.

Table 10 refers to frequency hopping radios that hop over the entire ISM band. The proportion of time, therefore, that the hopping radio spends within one of the LMS bands is in the order of Ft/10. Thus, for example, for frequency hopping devices which are constantly transmitting, from Table 4, this relates to 54 devices with respect to 44 from Table 10.

Similarly, for frequency hopping devices that are transmitting 10% of the time (Ft = 0.1 in Table 10), 440 devices can co-exist in an area. The number that can co-exist with the LMS system is 540 (from Table 4 for Ft = 0.01).

Table 11 refers to devices that hop over 12.775 MHz. If that band encompasses an LMS band, then the proportion of time spent in the LMS band is about 25%. Thus, from Table 4, 21 devices can be tolerated by the LMS system compared to 20 devices which can theoretically co-exist.

It can be seen therefore, that the number of Part 15.247 frequency hopping devices that can co-exist together is less than the number that can co-exist with the LMS system.

9. Quantities of Part 15 Devices

8.1. Unit Area

In a suburban environment, the radius of the "unit area" will be in the order of 8 miles[7]. This reduces to about 4 miles for more urban environments. Thus the suburban unit area is in the order of 200 square miles.

8.2. Cordless Phones

From Table 2, in the LMS sub-band, assuming a 1% usage, there can be 8000 Part 15.247 devices in the unit area. Assuming that the Part 15.247 cordless phone device occupies 4 MHz, then there can be 16000 in the LMS sub-bands alone. There is then at least 12 MHz additional band available outside of the LMS sub-bands. Thus there can be, at a minimum, at least 40,000, Part 15.247 cordless phones in a 200 square mile area, i.e. 200 Part 15.247 phones per square mile. The number will be higher because a higher density of devices can be present outside of the LMS sub-band.

If the case of the phone taken outside is considered, from Table 5 shows that 78 outside Part 15.247 phones per square mile is acceptable.

From Table 3, the number of Part 15.249 cordless phones is 74000 in the unit area. This equates to at least 2220 Part 15.249 phones per square mile.

From these figures, and from the analysis in Section 7, it is clear that the cordless phone type devices will reach a point of mutual interference before the interference to LMS will be a problem.

8.3 Indoor Devices

The analysis for any indoor device will be similar to that presented for the phones with the exception that the percentage of time spent transmitting will differ. If 10% is assumed, then following a similar analysis to that for the cordless phones, the following results:

20 Part 15.247 devices
and 222 Part 15.249 devices per square mile.

[7]This assumes a 10 dB desensitization of the fixed site.

8.4 Outdoor Devices

In the case of outdoor devices it has been shown in Section 7 that the limit to the number of Part 15.247 devices is their mutual interference. This limits the devices to about 0.6 per square mile, for direct sequence devices, and about 2 per square mile, for frequency hoppers, assuming a 10% transmission duty cycle.

Table 6 shows that about 2300, Part 15.249 devices can exist in an LMS sub-band, assuming 10% transmissions. Thus, for devices such as meter readers and telemetry, at least 79 such devices could exist per square mile.

10. Discussion.

In a suburban environment, the radius of the area will be in the order of 8 miles[8]. This reduces to about 4 miles for more urban environments. The Tables given in this paper give the quantities of Part 15 devices that could theoretically be tolerated within such areas. It must be stressed that these numbers only refer to those devices transmitting within the LMS sub-bands, and hence, if all the various types of Part 15 devices are considered, much higher numbers can be tolerated

The results show that devices that transmit on a low duty cycle, even if transmitting 1W, can be virtually ignored. Between 3000 and 10000 indoor 1W devices, transmitting 1% of the time, in the LMS sub-band, are required before the LMS system will experience a 10% probability of loss of location. The equivalent number for the outdoor devices is between 170 and 540.

Furthermore, the results show that the number of Part 15 devices that can co-exist, under similar conditions, is much less, in the case of direct sequence spread spectrum devices, and less, in the case of frequency hopping devices, as those that can be tolerated by the LMS systems.

From these results it is clear that the effect of the LMS systems will not cause a dramatic decrease in the number of Part 15 devices in the field, and similarly the number of cases where the LMS system operators will require the co-operation of a Part 15 user/supplier in order to resolve any harmful interference will be very limited.

[8]This assumes a 10 dB desensitization of the fixed site.

Annex A

Derivation of Expressions for Probability of Blocking

1. Probability of Blocking of One Fixed Site

Consider a receiving site with a circular coverage area of unit radius, area π, as shown in Figure 1:

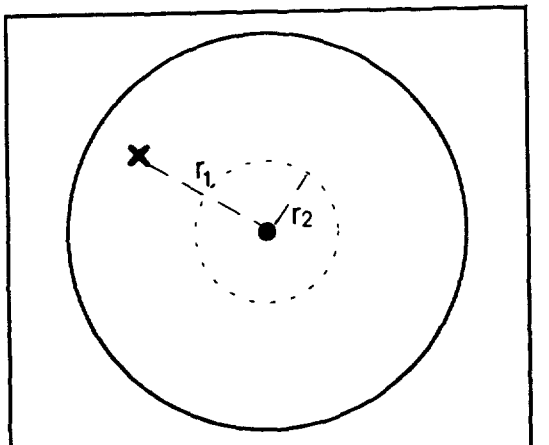

Figure 1 - Area of unit radius

For the wanted vehicle at distance r_1 from the site, then any interferer that is within a distance r_2 of the site is capable of blocking the transmissions if :

$$\frac{r_1}{r_2} \geq NFR \qquad (1)$$

where NFR is the near-far-ratio.

Assuming an even distribution of vehicles and interferers over the area,

The proportion of units within the circle, radius r_2 is: $\frac{\pi(r_2)^2}{\pi} = r_2^2$

From (1)

$$(r_2)^2 = \left(\frac{r_1}{NFR}\right)^2 \qquad (2)$$

This is the probability, P_{NFR} , that an unwanted transmission is inside the NFR and hence capable of blocking the wanted.

Probability that the wanted vehicle is close to r_1 is shown in Figure 2,

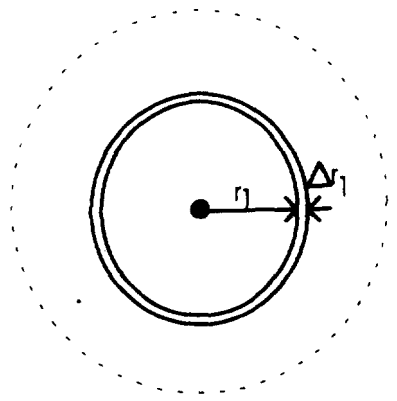

Figure 2 - Wanted vehicle position

Probability, P_{r1}, that the wanted vehicle is close to r_1 is:

$$P_{r1} = \frac{1}{\pi}[\pi(r_1 + \Delta r_1)^2 - \pi r_1^2] = 2r_1\Delta r_1 \qquad (3)$$

Hence, probability that wanted vehicle is at r_1 and unwanted transmission is within the near far ratio, is the product of (2) and (3):

$$P_{NFR}P_{r1} = \frac{2r_1\Delta r_1 r_1^2}{(NFR)^2} = \frac{2r_1^3}{(NFR)^2}\Delta r_1$$

Integrating wrt r_1 :

$$P_{bNFR} = P_{NFR}P_{r1} = \int_0^1 \frac{2r_1^3}{(NFR)^2}\partial r_1 = \frac{1}{2(NFR)^2} \qquad (4)$$

Let us now consider the probability that the unwanted radio is transmitting at the same time as the wanted.

Assume that the transmission time of the Part 15 device is greater than that of the LMS location pulse, and let *Ft* be the average fraction of time that the Part 15 device is transmitting.
Let there be *N* Part 15 devices in the unit area circle.

The chance of exactly *n* unwanted transmissions being present is given by the binomial probability:

$$P_{(n)} = \frac{N!}{n!(N-n)!}Ft^n(1-Ft)^{(N-n)} \qquad (5)$$

If there are n unwanted transmissions, then the probability that they do not block the wanted is $(1-P_{bNFR})^n$.

Thus, the probability that they do block, i.e. within the NFR, is:

$$1-(1-P_{bNFR})^n$$

The probability of blocking, P_b, is the product of the probability of there being n unwanted transmitters, $P_{(n)}$, and the probability that they are within the NFR.

Hence
$$P_b = \sum_{n=0}^{N}(1-(1-P_{bNFR})^n)P_{(n)} \tag{6}$$

Expanding,
$$P_b = \sum_{n=0}^{N}P_{(n)} - \sum_{n=0}^{N}(1-P_{bNFR})^n P_{(n)}$$

Now $\sum_{n=0}^{N}P_{(n)} = 1$

Thus,
$$P_b = 1-\sum_{n=0}^{N}(1-P_{bNFR})^n P_{(n)} \tag{7}$$

The probability that there are exactly n unwanted pulses is $P_{(n)}$, given by equation (5).

$$P_b = 1-\sum_{n=0}^{N}\left(1-\frac{1}{2(NFR)^2}\right)^n \frac{n!}{n!(N-n)!}Ft^n(1-Ft)^{(N-n)} \tag{8}$$

It can be noted that the binomial distribution can be often approximated by the Poisson distribution[9]. Hence, (8) can be re-written:

$$P_b = 1-\sum_{n=0}^{N}\left(1-\frac{1}{2(NFR)^2}\right)^n \frac{(NF_t)^n}{n!}e^{-NF_t} \tag{9}$$

For the case of $Ft = 1$,

$$P_b = 1-\left(1-\frac{1}{2(NFR)^2}\right)^N \tag{10}$$

[9]This is easier for calculations.

2. Frequency Hopping

In the case of frequency hopping radios, there is an added probability of the chance that the channel chosen by the wanted radio is already occupied.

Let there be M channels. The probability that a radio chooses a particular channel is $1/M$.

The probability that the radio is not on a particular channel is therefore $(1-1/M)$.

For n radios, the probability that they are not on a particular channels is therefore $\left(1-\frac{1}{M}\right)^n$

Thus, the probability that the channels is occupied, P_{OC}, is:

$$P_{OC} = 1-\left(1-\frac{1}{M}\right)^n \tag{11}$$

In the case of frequency hopping radios, the probability of blocking is given by including the probability of the channel being occupied into equation (6).

Thus,

$$P_{bFH} = \sum_{n=0}^{N}\left(1-(1-P_{bNFR})^n\right)\left(1-\left(1-\frac{1}{M}\right)^n\right)P_{(n)} \tag{12}$$

$$P_{bFH} = \sum_{n=0}^{N}\left(1-\left(1-\frac{1}{2(NFR)^2}\right)^n\right)\left(1-\left(1-\frac{1}{M}\right)^n\right)\frac{(NF_t)^n}{n!}e^{-NF_t} \tag{13}$$

3. Probability of Blocking at Multiple Sites

In order to obtain a location using time of arrival techniques, it is necessary to have at least four stations reporting. In order to obtain accurate location in practical conditions, the more stations reporting the better so as to compensate for the effects of blocking and multipath.

If there are S sites that receive the location burst, then the location will be lost if less than four sites are not blocked. If each site has a probability of P_b that it is blocked, then the probability that s or more sites are blocked is, (from the binomial distribution):

$$P_{(s+)} = \sum_{s}^{S}\frac{S!}{s!(S-s)!}P_b^s(1-P_b)^{S-s} \tag{14}$$

If there are 6 sites that receive the location burst then S = 6 and s = 3, i.e. if 3 or more sites are blocked then the location is lost.

Table 1A shows the value of P_b required for a 10% probability of loss of location against the number of sites, S.

Table 1A
Required probability of site blocked, Pb for 10% lost locations

No sites	4	5	6	7
Pb=	0.026	0.115	0.2	0.28
P(no loc)	0.10	0.10	0.10	0.10

From Table 1A it can be seen that if there are 6 sites that receive the location burst, then 10% of the locations will be lost if the probability of blocking of each site is 20%.