Interference, Sensitivity and Capacity Calculations for Measurement-based Wireless Access Spectrum Sharing

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Abstract- In this paper, interference caused by multiple uncoordinated low-power wireless access system transmitters to fixed point-to-point microwave receivers is analyzed. The analysis shows that the density of wireless access system users that can share spectrum with point-to-point microwave system depends critically on the propagation relation, the threshold of detecting energy from point-to-point transmitters, and the allowable interference into point-to-point receivers. It is found that for reasonable assumptions of point-to-point link, wireless access system, and propagation parameters, a wireless access system employing measurement-based interference avoidance must detect energy of point-to-point transmissions far below the thermal noise floor of the wireless access system receivers which would increase their complexity. This work is targeted towards understanding the implications to local exchange networks of wireless system alternatives that could provide access to those networks.

I. Introduction

To ease the shortage of radio frequency spectrum, it is sometimes possible for two dissimilar radio services to share the same frequency band. It has been proposed that low-power wireless systems used to access local exchange networks share spectrum at 2 GHz., which is currently used in the point-to-point microwave radio service.

In order to avoid mutual interference between the point-to-point radios and the wireless access system, it is necessary to electromagnetically isolate the two services. Since point-to-point radio installations generally operate full-time from fixed locations, and are incumbent in the bands of interest for wireless access, methods must be devised which prevent the new wireless access ports and their associated portable units from operating on frequencies in interference-producing locations. A few of the ways of achieving the required isolation are:

- Prediction based on propagation: Interference from wireless access system ports and portables into point-to-point radios, and vice versa, can be predicted based on path loss models to spatially isolate the two services. However, the actual path loss depends on a large number of variables. Some of these parameters, such as transmitter power, antenna pattern, receiver threshold, interference threshold, and free space path loss may be quantifiable. However, the complexity and variability of the propagation characteristics in actual operating environments may make prediction of the interference levels very difficult. Fixed antenna mounting arrangements and nearby structures can significantly change the pattern that was determined by calculation. Furthermore, objects at some distance from the involved stations which are reflecting, scattering and absorbing microwave energy can significantly alter propagation expectations from the predictions made by available models. This is further complicated by the size and shape of the wireless access system coverage area and the unpredictability of the location of portables within it. The propagation loss between wireless access units and point-to-point radios will vary over a wide range. Therefore, if electromagnetic isolation between point-to-point radios and wireless access units is to be achieved based on propagation models, conservative calculations must be used, leading to less efficient sharing of spectrum.

- Measurement-based: Wireless access ports and portables monitor the presence of energy from fixed point-to-point transmitters and infer the receiver frequency before selecting frequencies for their use. Since spectrum avoidance based on measurements uses actual path loss, conservative estimates are not needed. This leads to more efficient sharing of spectrum. In addition, no preplanning of frequency assignment is necessary.

- A combination of prediction and measurements[1].

II. Measurement-Based Spectrum Sharing

In measurement-based spectrum sharing, wireless access ports and portables detect the presence of energy from point-to-point radio transmitters and infer the corresponding point-to-point receiver frequencies to avoid. Though proposals for measurement-based techniques exist for frequency sharing[2], the effect of multiple uncoordinated wireless access transmissions on point-to-point receivers has received little consideration. Transmission from a single low-power wireless access transceiver whose receiver is just below the threshold of detecting point-to-point microwave energy may not alone cause interference to a point-to-point receiver. However, multiple wireless access transceiver transmissions, each one oblivious to both point-to-point microwave transmitter energy and other wireless access transceiver transmissions, may cause collective interference to point-to-point receivers that exceed acceptable limits. To illustrate this point, let us consider detecting energy from a point-to-point microwave system transmitting a 1 W signal (30 dBm) in a bandwidth of 10 MHz. Since a wireless access system is more likely to be designed to share spectrum when it is in the sidelobe of the point-to-point microwave antenna pattern, we consider detecting energy from point-to-point transmitters in the sidelobe. The gain of the microwave antenna in the sidelobe is assumed to be 0 dBi. In the following table, we calculate the path loss when the signal level from the point-to-point transmitter is at the thermal noise floor of the receiver detecting the microwave energy. A wireless access system

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receiver with a 350 kHz bandwidth and a microwave energy detection system with 10 MHz receiver bandwidth are considered.

Point-to-point TX power in 10 MHz bandwidth	30	dBm
Point-to-point TX and RX antenna gain (side lobes)	0	dBi
Port/portable receiver antenna gain	0	dBi
Loss when power is intercepted in 350 kHz bandwidth	15	dB
Effective transmit power seen by 350 kHz receiver	15	dBm
Effective transmit power seen by 10 MHz receiver	30	dBm
Noise floor at 350 kHz BW (4 dB noise figure)	-115	dBm
Noise floor at 10 MHz BW (4 dB noise figure)	-100	dB
Path loss at the threshold of detection	**130**	**dB**

Table 1. Path loss calculation at the threshold of detection of wireless access receiver

From the table we see that whether a wireless access system with a 350 kHz receiver bandwidth or a microwave energy detection system with a 10 MHz receiver bandwidth is used (as long as the receiver antenna gains and receiver noise figures are the same for both receivers and the point-to-point transmit spectrum is relatively flat), when the path loss is 130 dB the microwave signal level is at the thermal noise floor of the receiver. Let us calculate the interference to the microwave receiver from uncoordinated wireless access system transmissions at distances corresponding to this path loss. It is assumed that wireless access system portables transmit 100 mW peak and 10 mW average power.

Portable peak power	20	dBm
Portable antenna gain	0	dBi
Noise floor at 10 MHz (2 dB noise figure)	-102	dBm
Peak power received from one wireless access system transmission at 130 dB path loss	-110	dBm
Average power received from 16 such simultaneous uncoordinated transmissions	-108	dBm

Table 2 Interference from portables at the threshold of detection

The interference criterion for private point-to-point microwave radios (TIA Bulletin TSB 10-E) states that the interference from all other users will cause no more than 1 dB degradation to the point-to-point radio threshold[3]. If this criterion is adhered to, the requirement will be violated when the total interference exceeds -108 dBm. Sixteen or more simultaneous transmissions from wireless access system portables, all at locations corresponding to 130 dB path loss, will cause the average interference to exceed -108 dBm. On the other hand, if energy from point-to-point transmitters can be detected with a higher sensitivity, the path loss at the threshold of detection will be higher and a higher density of users can be supported. The density of users and the threshold of detecting energy from point-to-point transmitters depend on a number of point-to-point microwave and wireless access system parameters. In the next section, we formulate an expression for the interference between wireless access systems and point-to-point radio systems in a general fashion and derive relationships among various parameters.

Interference and Sensitivity Calculations

In this section, we formulate an expression for interference between point-to-point radios and wireless access systems. The purpose of the formulation is not to define real geographic exclusion areas based on path loss models to aid frequency planning. However, for the propagation model we assume, these calculations shed light on the interrelationships among certain key wireless access system and point-to-point radio parameters. The various parameters used in the analysis are summarized below.

$P_{\mu w}$	point-to-point transmit power
P_{hs}	average portable transmit power
ρ_{hs}	portable density per rf channel per km^2
l_k	signal level at 1 km distance from a 0 dBm transmitter
k	Boltzmann's constant
α	path loss exponent where path loss is proportional to distance$^{\alpha}$
η	allowable interference into point-to-point receiver with reference to thermal noise level
$B_{\mu w}$	bandwidth of the point-to-point receiver
B_{wa}	bandwidth of the wireless access system
R_{bw}	bandwidth ratio - point-to-point microwave radio to wireless access system($B_{\mu w}/B_{wa}$)
P_{therm}	thermal noise level in point-to-point receiver ($kTB_{\mu w}$)
r	distance from portable to point-to-point receiver in kilometers

The antenna of the point-to-point radio is assumed to have a keyhole pattern as shown in figure 1. Parameters pertaining to the point-to-point antenna pattern are given below.

g_m	gain of the point-to-point antenna in main beam (bore sight)
g_s	gain of the point-to-point antenna in the side lobe
β	width (in radians) of main beam
r_{exn}	exclusion zone radius in main lobe in kilometers
r_{exs}	exclusion zone radius in side lobe in kilometers

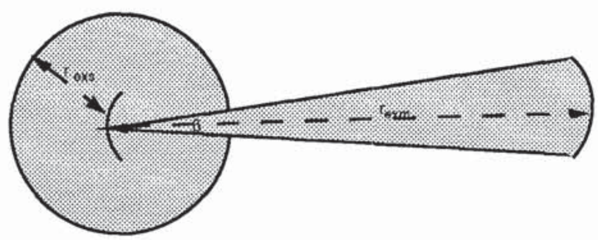

Figure 1. Idealized exclusion area for interference analysis

An exclusion zone is an area where energy from the point-to-point transmitter is detectable by the wireless access system. In this area, a wireless access system must avoid using the frequency of the point-to-point receiver. The idealized exclusion zone will resemble the point-to-point antenna pattern as shown in Figure 1. However, in a real environment, because of the variability of shadowing, reflection, scattering, etc., the actual exclusion zone will not have a well connected geometric shape, but will consist of non-contiguous areas where the point-to-point transmitted energy is detectable at a given time.

In the interference analysis, we assume a uniform density of wireless access system users over an infinite 2-dimensional plane. The ports and portables monitor the presence of point-to-point energy before selecting frequencies for their use. When point-to-point energy is detected, as in the case within the shaded area for the link under consideration, wireless access users refrain from transmitting at the frequency corresponding to the point-to-point receiver. Therefore, interference into this point-to-point receiver is caused by all wireless access users outside the exclusion area that are transmitting on frequencies within the point-to-point bandwidth.

Interference into the point-to-point receiver from all wireless access system portables outside r_{exs} in the sidelobe, assuming wireless access system users on all wireless access system channels within the point-to-point microwave bandwidth, is

$$\begin{aligned} P_{ins} &= R_{bw} P_{hs} \rho_{hs} g_s \int_0^{2\pi-\beta} \int_{r_{exs}}^{\infty} \frac{l_k r}{r^{\alpha}} dr d\theta \\ &= \frac{R_{bw} P_{hs} \rho_{hs} g_s (2\pi-\beta) l_k}{(\alpha-2) r_{exs}^{(\alpha-2)}} \end{aligned} \tag{1}$$

Similarly the interference into the point-to-point receiver from all wireless access system portables outside r_{exm}, in the main beam, assuming wireless access system portables on all wireless access system channels within the point-to-point bandwidth, is

$$\begin{aligned} P_{inm} &= R_{bw} P_{hs} \rho_{hs} g_m \int_0^{\beta} \int_{r_{exm}}^{\infty} \frac{l_k r}{r^{\alpha}} dr d\theta \\ &= \frac{R_{bw} P_{hs} \rho_{hs} \beta g_m l_k}{(\alpha-2) r_{exm}^{(\alpha-2)}} \end{aligned} \tag{2}$$

Therefore, the total interference is

$$P_{in} = \frac{R_{bw} \rho_{hs} P_{hs} l_k}{(\alpha-2)} \left(\frac{g_m \beta}{r_{exm}^{(\alpha-2)}} + \frac{g_s (2\pi-\beta)}{r_{exs}^{(\alpha-2)}} \right) \tag{3}$$

At the boundary of the shaded area, wireless access portables are at the threshold of detecting energy from the point-to-point transmitter. The power from the point-to-point transmitter into a wireless access system portable at this detection threshold is

$$P_{thr} = \frac{P_{\mu w} g_m l_k}{R_{bw} r_{exm}^{\alpha}} = \frac{P_{\mu w} g_s l_k}{R_{bw} r_{exs}^{\alpha}} \tag{4}$$

Therefore,

$$r_{exm} = r_{exs} \left(\frac{g_m}{g_s} \right)^{1/\alpha} = r_{exs} (R_{FB})^{1/\alpha} \tag{5}$$

where R_{FB} is the front-to-back ratio of the microwave antenna gain. Substituting for r_{exm} in equation (3), the total interference into the point-to-point receiver from all portables outside the exclusion area is then

$$P_{in} = \frac{R_{bw} \rho_{hs} P_{hs} l_k g_s}{(\alpha-2) r_{exs}^{(\alpha-2)}} \left((2\pi-\beta) + \beta (R_{FB})^{2/\alpha} \right) \tag{6}$$

In order to meet the interference criterion for the point-to-point receiver, this interference cannot exceed a limit. Let us assume this limit is equal to η times the thermal noise level of the point-to-point receiver. Therefore,

$$P_{in} = \eta P_{therm} = \frac{R_{bw} P_{hs} \rho_{hs} l_k g_s}{(\alpha-2) r_{exs}^{(\alpha-2)}} \left((2\pi-\beta) + \beta (R_{FB})^{2/\alpha} \right) \tag{7}$$

P_{in} is the total interference into the point-to-point receiver from all the portables in the point-to-point bandwidth. The factor $R_{bw} P_{hs} \rho_{hs}$ is the total radiated wireless access portable power per km^2 in the point-to-point receiver bandwidth. The two factors $\left[(2\pi-\beta)\right]$ and $\left[(\beta(R_{FB})^{2/\alpha}\right]$ represent the sidelobe and mainbeam contributions, respectively.

From equation (7), the exclusion radius in the sidelobe is

$$r_{exs} = \left\{ \frac{R_{bw} \rho_{hs} P_{hs} l_k g_s}{(\alpha-2) \eta P_{therm}} \left((2\pi-\beta) + \beta (R_{FB})^{2/\alpha} \right) \right\}^{1/(\alpha-2)} \tag{8}$$

Substituting this in (4), we get the point-to-point transmitter power received by wireless access system portables at the exclusion boundaries to be

$$\begin{aligned} P_{thr} &= \frac{P_{\mu w}}{R_{bw}} (g_s l_k)^{\frac{2}{(2-\alpha)}} \left[\frac{R_{bw} \rho_{hs} P_{hs}}{(\alpha-2) \eta P_{therm}} \right]^{\frac{\alpha}{(2-\alpha)}} \\ &\bullet \left[(2\pi-\beta) + \beta (R_{FB})^{2/\alpha} \right]^{\frac{\alpha}{(2-\alpha)}} \end{aligned} \tag{9}$$

The wireless access system portables must detect point-to-point transmitter power with a detection sensitivity P_{thr} and thus avoid transmitting at the point-to-point receiver frequency in order to meet the interference criterion given by equation (7).

The factor $R_{bw} \rho_{hs}$ is the number of active simultaneous users per km^2 that can share spectrum with a point-to-point channel, and therefore, represents the traffic supported in a shared environment. Denoting $C = R_{bw} \rho_{hs}$ as the traffic capacity in Erlangs/km^2/point-to-point channel, we see that

$$C \propto P_{thr}^{\left(\frac{\alpha-2}{\alpha}\right)} \tag{11}$$

$$C \propto \eta \tag{12}$$

C and P_{thr} are related to r_{exs} by

$$P_{thr} \propto r_{exs}^{-\alpha} \tag{13}$$

$$C \propto r_{exs}^{(\alpha-2)} \quad (14)$$

Equations (11),(12),(13), and (14) give the relationship among the capacity of active users that can be supported in a sharing environment, the required detection sensitivity, and the exclusion radius.

Even though the above derivation used portable density as a parameter, the relationships are valid for ports also when port power and port density are substituted for portable density and portable power, and l_k, which represents the path loss at 1 km, takes into account the port antenna height.

Let us assume the following typical values for point-to-point and wireless access system parameters.

$P_{\mu w}$	1W (30 dBm)
g_s	1 (0 dBi)
g_m	1000 (30 dBi)
β	0.1 (5.7°)
Bandwidth of the point-to-point channel	10 MHz
Bandwidth of the wireless access system	350 kHz
Average power for a portable	10 mw

Table 3. Typical parameters

For the above typical values, we calculate the detection sensitivity and exclusion radius as a function of capacity, l_k, α, and η

α	η (dB)	l_k (dB)	C	r_{exs} (kms)	P_{thr} (dB)
4	-4	-110	10	16.8	-143.
4	-4	-110	100	53	-163.
4	-4	-120	10	5.3	-133.
4	-4	-120	100	16.8	-153.
4	-4	-120	1000	53	-173
4	-4	-130	10	1.7	-123
4	-4	-130	100	5.3	-143
4	-4	-130	1000	16.8	-163
4	0	-130	1000	10.6	-155
4	10	-130	1000	3.3	-135
4	10	-130	10000	10.6	-155
3	-4	-130	10	9.7	-144
3	-4	-130	100	97	-174
3	0	-130	10	3.9	-132
3	0	-130	100	38.7	-162

Table 4. Traffic capacity C (in Erlangs/km^2/point-to-point channel) as a function of other parameters

III. Discussion

In the above table, α is the propagation constant, and η is the allowable interference into the point-to-point receiver with reference to its thermal noise level. Assuming a noise figure of 2 dB for the point-to-point receiver, an η of -4 dB corresponds to satisfying the interference criterion (TIA TSB-10E) that the interference from all wireless access users will cause no more than 1 dB degradation to the point-to-point receiver threshold. l_k is the signal level at 1 km from the transmitter if the transmitted power is 0 dBm. From the Hata model[4], assuming dipoles for the wireless access system and 150 m antenna height for the point-to-point station and 2 m antenna height for a portable, the path loss at 1 km is about 130 dB. The corresponding path loss for a port with 10 m antenna height is about 116 dB. C is the number of active users and therefore, the traffic in Erlangs that can be supported simultaneously in one point-to-point channel (10 MHz in our calculation) per km^2. In a real environment, exclusion radii cannot be defined; however, a larger r_{exs} indicates that wireless access systems have to avoid the point-to-point receiver frequency over a larger area. P_{thr} is the threshold at which the point-to-point energy must be detected and the corresponding point-to-point receiver frequencies avoided in order to meet the interference criterion. For a wireless access system with a 350 kHz receiver bandwidth, the thermal noise floor is about -120 dBm. From the table we make the following observations:

- The actual path loss relation (α and l_k) plays a crucial role in determining the feasibility of frequency sharing. If the propagation constant is below 4 or if the path loss at 1 km is below 120 dB, very few users can share spectrum with point-to-point radios for reasonable values of detection sensitivity.
- In order to support a high density of wireless access users, point-to-point transmitter energy must be detected at levels far below the thermal noise floor of the wireless access system. The required detection sensitivity increases more rapidly than does the allowable user density. For example, improving the detection sensitivity by 20 dB increases the user density only by a factor of 10.
- Capacity depends critically on the allowable interference into a point-to-point receiver. A higher allowable interference will permit a higher density of simultaneous wireless access system users. For example, increasing the allowable interference into point-to-point receivers by 10 dB increases the user density by a factor of 10
- In order to support the same density of users, ports will have to detect the point-to-point transmitter power at a higher sensitivity than by portables, even if the average power per user is the same since ports with higher antennas result in a lower l_k compared with that for portables.

The above analysis has assumed only a strict geometrical change of path loss with distance. In reality, additional path loss variability is caused by shadowing[5,6]. Simulation studies have shown that path loss variability results in a slight to moderate reduction in capacity than predicted by strict geometric relationship. However, the interrelationships among various parameters and observations made above still hold good.

For efficient sharing of spectrum, we need to take full advantage of the variability of path loss. Since path loss could change by several dBs over short distances, the variability can be exploited only by monitoring the point-to-point transmitted energy at the site of ports' and portables' operation. Therefore, for the most efficient sharing of spectrum, both ports and portables should monitor the microwave energy. However, the requirement that point-to-point energy should be detected much below the thermal noise floor implies that wireless access system receivers need to carry out very sensitive measurements, which will increase the complexity of the system.

In addition to the above considerations, a measurement technique warrants the following considerations:

- Since the point-to-point receiver frequencies are inferred from monitoring point-to-point transmit frequencies, non-standard offset and one-way links need to be treated differently.

- The monitoring receiver needs to differentiate between point-to-point microwave energy and wireless access system energy.

IV. Conclusions

This paper considered spectrum sharing between wireless access systems and point-to-point microwave systems by detecting energy from point-to-point transmitters and avoiding the use of point-to-point receiver frequencies by the wireless access system. We analytically formulated relationships among the wireless access system user density, required detection sensitivity, propagation constant, and allowable interference into the point-to-point receiver. Analysis indicates that for reasonable assumptions of point-to-point link and propagation parameters, a wireless access system must detect energy from point-to-point transmissions far below the thermal noise floor of the wireless access system. This would mean that ports and portables will need to carry out very sensitive measurements; this requirement would have an impact on the complexity of ports and portables. The complexity of carrying out sensitive measurements by ports and portables may warrant alternative techniques for detecting the presence of point-to-point links.

The coordination criterion for fixed point-to-point microwave systems needs to be revisited. Private point-to-point radios coordinate their systems such that interference from all other users will cause no more than 1 dB degradation to the point-to-point receiver threshold. If the coordination is based on the requirement that fades should not cause system outage for more than a specified amount of time per year (so that the system availability is maintained at a very high percentage), a higher interference may be tolerated for short links. A higher allowable interference will permit a higher density of simultaneous wireless access users.

V. Acknowledgment

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