A White Paper

on the Exploitation of “Spectrum Holes” to Enhance Spectrum Efficiency

Submitted by Motorola

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Introduction

Recent measurements [1] of spectrum occupancy as a function of time have shown that, at a single location, some bands of frequencies have no observable activity for significant periods of time (seconds to minutes). Other measurements, for example [2], have shown wide variability in long-term (days) average spectrum occupancy as a function of frequency. In these measurements, "spectrum occupancy" is based upon detectable received power in the resolution bandwidth of a spectrum analyzer. If the received power is below a threshold, the spectrum is declared to be unoccupied[1]. Based on these measurements it has been conjectured that it may be possible to improve overall spectrum utilization using advanced spectrum sharing technologies. Specifically, the DARPA NeXt Generation Communications program [1] has set a goal of a twenty times improvement in spectrum efficiency for military communications equipment using advanced spectrum sharing technologies. This white paper has been prepared by Motorola to discuss issues affecting spectrum sharing technologies that exploit spectrum holes. Specifically, problems associated with declaring a band of frequencies available for use are addressed in detail.

What is a "spectrum hole"?

A *spectrum hole*[2] is a band of frequencies that are not being used by the primary user of that band at a particular time in a particular geographic area. Since the spectrum hole is not being used by the primary user, the spectrum hole might be available to a user not being serviced in a different band due to congestion.

A spectrum hole cannot be identified by a single measurement of spectrum occupancy at a single geographic location. To correctly declare a band of frequencies available for use by a non-primary user, the effect of the contemplated use on all primary users of the band within range of the contemplated transmission must be considered. If the contemplated use of the band degrades the performance of any ongoing or future planned use of the band by a primary user, the band is not a spectrum hole. While the term "spectrum hole" implies that the spectrum is not being used at all, in reality, what is being considered is dynamic co-channel spectrum sharing based on time, geography and frequency. Accordingly, to determine whether a portion of spectrum is usable at any time by the non-primary user it is necessary to determine how much interference can be added by the non-primary user while having no perceptible impact on the primary user.

Consider the simplified system illustrated in Figure 1. Ignore, for now, shadow fading as well as fast fading. Two base stations, denoted "A" and "B", and two mobile users, denoted "a" and "b", are illustrated. The circles surrounding the base stations illustrate three different ranges, r_1, r_2, and r_3. The range r_1 is the maximum range (with all the appropriate assumptions regarding transmit power, noise figure, and so on) for reliable communications to a user. The range r_2 is the maximum range that the transmission will cause significant degradation to another user, and the range r_3 is the maximum range for which the transmitted signal is detectable. The relative magnitudes r_2 and r_3 depend on the modulation used for information transfer and the signal detection method used

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[1] Some modulation schemes, e.g. spread spectrum, operate at very low signal-to-noise power ratio in the transmission bandwidth and are therefore difficult to detect using normal radiometric techniques. Other detection techniques are known for detecting these types of signals. Thus, the published spectrum occupancy results must be interpreted with knowledge that wideband low power spectral density signals may, in fact, not be observed.

[2] The terminology "spectrum hole" was used by Dr. P. Kolodzy in his presentation to the FCC Technological Advisory Council II on December 5, 2001 and also in [1].

to search for spectrum holes. It is possible that $r_2 > r_3$ under certain conditions; this could be the case when direct-sequence spread-spectrum modulation is used and radiometric signal detection is used. Suppose next that base station "A" is transmitting to mobile "a". This transmission can be reliably received by mobile "a" but not even detected by mobile "b" or base "B". Thus, measurements by mobile "b" or base "B" would declare the frequency to be a spectrum hole when, in fact, if base station "B" began to use this frequency, interference with ongoing transmissions to mobile "a" would occur. To correctly declare a frequency to be a spectrum hole for potential use by base "B", measurements must be made at all locations that would receive unacceptable interference from base "B" if those transmissions were to occur. In Figure 1, for example, measurements must be made at all locations within the circle with radius r_2 centered at base "B" for the frequency to be declared a spectrum hole for base B. The point of this illustration is simply that unacceptable interference may be created by a transmission at locations distant from the desired receiver and therefore that the spectrum must be measured at locations other than just the intended receiver and transmitter.

In general, the declaration that a band of frequencies is a spectrum hole is a function of the use being contemplated for that band as well as the current usage of the band. The potential user of the spectrum must assure that his transmissions will not interfere with primary users of the band at all locations where that interference might occur. To quantify this concept, consider again the systems of Figure 1 and, as before, let base "A" and mobile "a" be the primary user of the band and let mobile "b" and base "B" be potential non-primary users of the band. Let $P_{r,A}$ and N_A denote the desired power and interference (including thermal noise) respectively received by mobile a. Let $I_{B,A}$ denote the interference caused by base "B" at mobile a. Assume that path loss is proportional to $1/r^4$ and that the required received power to achieve reliable communications for mobile "b" is $P_{r,B} \equiv P_{r,A}$. Let the range from base "B" to mobile "b" be denoted by r and the range from base "B" to mobile "a" be denoted r'. With these assumptions and definitions, the degradation (in decibels) in the $SINR$ at mobile "a" caused by base "B" transmitting to mobile "b" is given by

$$\delta = 10\log_{10}\left(\frac{\dfrac{P_{r,A}}{N_A}}{\dfrac{P_{r,A}}{N_A + I_{B,A}}}\right) = 10\log_{10}\left(\frac{N_A + I_{B,A}}{N_A}\right) = 10\log_{10}\left(\frac{N_A + P_{r.,B}\left(\dfrac{r}{r'}\right)^4}{N_A}\right) = 10\log_{10}\left(1 + \frac{P_{r.,B}}{N_A}\left(\frac{r}{r'}\right)^4\right).$$

This relationship defines an <u>area</u>, specifically a circle with radius r', in which the spectrum must be unused if the spectrum hole is to be declared available for use by a non-primary user. This area will be called an *exclusion zone.* If the primary user is outside of this exclusion zone, degradation to its communications will be less than δ decibels given that the primary user's signal-to-interference power ratio is $P_{r,A}/N_A$ in the absence of the interference. The radius of the exclusion zone is dependent on the amount of degradation of $SINR$ that is acceptable to a primary user of the spectrum and on the assumed path loss exponent (assumed equal to 4 in the equation above). Figure 2 illustrates the radius of the exclusion zone for path loss exponents of 2, 3, and 4 and for degradations between zero and 2 decibels. These curves show that, for a path loss exponent of 4, a circle centered on the non-primary user's transmitter of radius twice the range to the non-primary user's receiver must be unused by the primary user if degradation is not to exceed 0.5 decibel. The plots in

Figure 2 were calculated assuming that the required $SINR$ for reliable communications[3] is equal to +3 dB; the specific value of $SINR$ will vary depending on the system being considered.

Shadowing is another physical phenomenon affecting the identification of spectrum holes. Consider the geographic scenario of Figure 3. Primary users "A" and "a" as well as non-primary users "B" and "b" are illustrated. The primary transceiver "A" is transmitting to primary transceiver "a" and transceiver "B" is blocked from that transmission by the obstruction. Therefore, transceiver "B" does not detect transceiver "A" and might declare the spectrum as unused when, in fact, transmissions by transceiver "B" would degrade reception at transceiver "a".

The concept of exclusion zones is also applicable to cooperative relay systems. An exclusion zone surrounding each potential non-primary user's transmitter is defined to be the area in which primary user's communications would be unacceptably degraded if the non-primary user's transmitter were activated. Measurements must assure that the spectrum is unused *throughout the exclusion zone* before the non-primary user is permitted to use the spectrum.

Issues affecting the identification of "spectrum holes"

The identification of spectrum holes for possible exploitation using a fast-dynamic radio resource manager is affected by many factors. Some of these factors are:

- Hidden terminal problem: Received power measurements at a single location do not necessarily indicate that it is possible to use a band of frequencies without degrading the performance of a primary user. Received power measurements over the exclusion zone of the anticipated transmission is a more reliable indicator of spectrum availability. The hidden terminal problem is discussed in more detail in the previous section.
- Intended use of spectrum by non-primary user: The geographic extent of the exclusion zone is a function of the anticipated transmit power of the non-primary user. The extent of the exclusion will be smaller if the intended use is to communicate with a relay station meters away than if the intended use is to communicate high-speed data over a much longer range. The non-primary user must sense primary user activity over the entire geographic extent of the exclusion zone before he may transmit.
- Antenna directionality and gains: The extent of the exclusion zone is directly related to the received power from the non-primary user affecting the primary user. This received power is affected by the antenna patterns of both the primary and non-primary users.
- Detector sensitivity: Primary-user activity over the entire exclusion zone must be estimated. The number and locations of sensors required to detect this activity is a function of the sensitivity of the sensors themselves as well as the characteristics of the sensor antennas. If the sensor sensitivity was adequate, it is conceivable that a single sensor co-located with the non-primary user's transmitter could be sufficient. However, it is unlikely that radiometric detection techniques could achieve the required sensitivity so that a sensor array would be required to adequately sense activity over the exclusion zone. Detector sensitivity is, of course, also affected by the noise figure of the sensor radio frequency circuitry. Motorola notes that techniques are known that achieve detection sensitivities superior to the sensitivities of a classical radiometer.

[3] For simplicity, the required $SINR$ for both users is assumed to be the same. A more complex formula could easily be derived if $SINR$ was different for the two users.

- Shadowing As illustrated in Figure 3, the effectiveness of the sensor is a function of the details of the relative locations of the sensor, the primary user, and physical obstructions. Accounting for shadowing by the dynamic radio resource manager will require real-time feedback mechanisms and will be a significant design challenge.
- Path loss details: As illustrated in Figure 1 and Figure 2, the geographic extent of the exclusion zone is strongly a function of the path loss between all users and anticipated users. The prediction of path loss for use in dynamic system control is difficult. Path loss depends on the terrain details that are most often not known at the controller. Therefore, real-time feedback mechanisms are needed to create a path loss database that could be used in the estimation of the exclusion zone.
- Transmission formats: The detectability of signals is affected by modulation details. For example, it is possible to design waveforms that appear as thermal noise to the sensor. Waveforms designed in this manner are called Low Probability of Detection (LPD) waveforms. Their use in a system where exploitation of spectrum holes is desired will be problematic. Many next-generation cellular systems will use direct-sequence spread spectrum technology designed for operation at very low signal-to-noise power ratios in the full transmission bandwidth. These waveforms will be difficult to detect using radiometric techniques. Also, non-continuous waveforms (e.g. TDMA) may be more difficult to detect than continuous waveforms.
- Occupied “Spectrum Holes”: Although the term “spectrum hole” implies that the band is not being used at all, the usability of the band requires only that the degradation to a primary user due to the non-primary user is below a predefined threshold that will ensure negligible to no impact on primary services.
- Exclusion Zones for Cooperative Relay Systems: Mature cooperative relay systems [3][4] will operate using very low transmit powers. Thus, the exclusion zones for these transmitters become very small and spectrum holes may be detected by a single sensor at the non-primary user’s transmitter.
- Prediction of Future Use: Suppose that a spectrum hole could be reliably detected over a particular geographic area at a particular instant in time. This knowledge is valid only for that instant in time and does not indicate that the spectrum hole would still exist at any future time. Thus, any spectrum sharing strategy based on the identification of spectrum holes must also include a process for continuous monitoring of the spectrum hole during the non-primary user’s transmission and for terminating the non-primary user’s transmissions if a primary user has need for the spectrum.

Motorola concludes that the identification and exploitation of spectrum holes will be difficult. Simplified approaches should be investigated that may yield some of the desired gains in spectrum efficiency. Simplified approaches might include hybrid systems that utilize a combination of ad hoc and classical cellular networking. Complex signal processing technology for sensing spectrum availability might be placed in cellular base stations. Also, ongoing research programs, for example [6], are investigating enhanced spectrum management concepts that combine third generation cellular architectures with broadcast systems with the goal of more efficient spectrum utilization. These advanced spectrum sharing procedures make use of a centralized radio resource manager. Motorola suggests that a combination of centralized and decentralized radio resource management may provide gains in spectrum efficiency and may be an effective interim step towards totally decentralized spectrum management.

Motorola supports the conjecture that radio systems having learning ability, i.e. Cognitive Radios [5], may be required to effectively exploit spectrum holes. Specifically, Mitola [5] has suggested that future Cognitive Radio systems will be highly complex and will have time-varying needs that will be difficult to meet using pre-defined control mechanisms. Radio systems having learning ability may be able to dynamically modify their own control procedures to respond to needs that could not be anticipated during initial system design. For example, the bandwidth of spectrum holes may vary as a function of location. A Cognitive Radio may be able to learn a new set of bandwidths when moved to a new location and adapt the detection and frequency management procedures accordingly. While research efforts for Cognitive Radio, cooperative relay networks (ad hoc networks), and fast dynamic radio resource management have been ongoing for some time, much additional research is required before these concepts will be commercially viable.

References

[1] Paul Kolodzy et al., "NeXt Generation Communications: Kickoff Meeting", DARPA, October 17, 2001.

[2] F. H. Sanders and V. S. Lawrence, "Broadband Spectrum survey at Denver, Colorado", U.S. Department of Commerce, National Telecommunications and Information Administration technical report, NTIA Report 95-321, September 1995.

[3] Timothy J. Shepard, "Decentralized Channel Management in Scalable Multihop Spread-Spectrum Packet Radio Networks", Ph. D. dissertation, Laboratory for Computer Science, Massachusetts Institute of Technology, July 1995.

[4] Piyush Gupta and P.R. Kumar, "The Capacity of Wireless Networks," *IEEE Transactions in Information Theory*, Vol. 46, No. 2, March 2000.

[5] Joseph Mitola III, "Cognitive Radio: Making Software Radios More Personal", *IEEE Personal Communications*, Vol 6, No 4, August 1999.

[6] European IST "OverDRiVE" program, "Spectrum Efficient Uni- and Multi-cast Services Over Dynamic Multi-Radio Networks in Vehicular Environments", IST-2001-35125. http://www.comnets.rwth-aachen.de/~o_drive/index.html

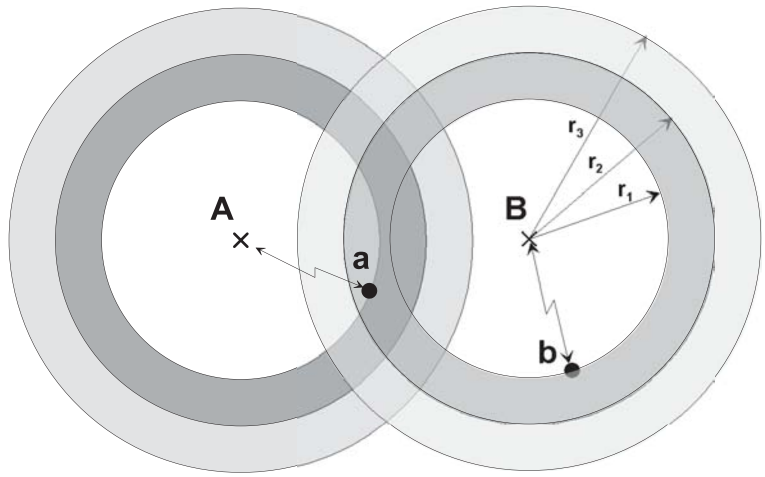

Figure 1. Illustration that activity detection at a single location is not sufficient to declare a frequency to be a spectrum hole.

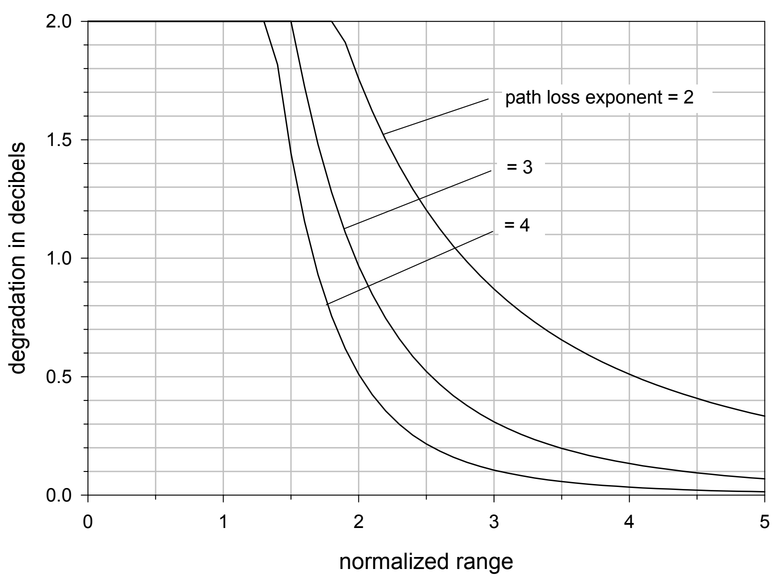

Figure 2. Normalized range r'/r from potential non-primary user of spectrum hole that must be unused by primary user in order to declare the spectrum hole available. Path loss exponent is a parameter.

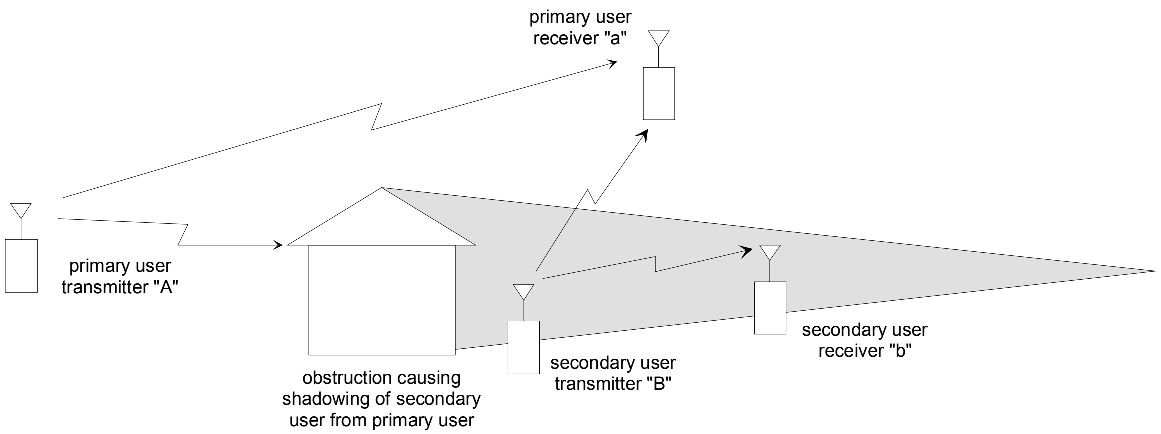

Figure 3. Shadowing of the non-primary user from the primary user may cause incorrect assessment of spectrum availability.