Cellular Systems and Rotating Radar Using the Same Spectrum

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***Abstract*—Spectrum-sharing with radar often means operating outside "exclusion zones" near the radar. However, it is technically possible for cellular systems to operate close to radar at data rates that are high on average without causing harmful interference simply by adjusting dynamically as the radar rotates. Despite fluctuations in data rate, cellular quality of service is sufficient for the applications that generate the vast majority of Internet traffic. This is an example of how "gray space sharing" can make more efficient use for spectrum; cellular devices operate on a secondary basis in spectrum that is *not* "unused." Although technically possible, this form of sharing poses new policy challenges. Particularly in cases where there are multiple entities operating primary systems and multiple entities operating secondary systems in the same spectrum, a new form of governance is needed to prevent, detect, and respond to harmful interference.**

Keywords: radar; cellular; spectrum sharing; primary-secondary sharing, gray space; white space; opportunistic

I. INTRODUCTION

There is growing pressure to support more and more communications within those spectrum bands that are most conducive to operating a cost-effective wireless system. A large part of that pressure will come from demand for cellular data services [1]. Many people assume that the only way to meet this need is to find an "unused" block of spectrum, and make it available for use. For example, a spectrum block within the frequencies allocated to television and within a geographic region that is far from any TV coverage area might be viewed as unused, and thus be made available for secondary use, as occurred in the TV "white space" rulings [2]. There is certainly great value in putting spectrum that is truly unused to work, but there are many ways to share spectrum and thus many ways to support more communications that go beyond simply finding unused spectrum [3, 4]. We refer to this as "gray space" sharing. For example, it has been shown that even in spectrum that is occupied by cellular systems with 100% utilization, there are ways in which other devices can operate on a secondary basis without having any impact on the cellular system's capacity or quality of service [5, 6, 7]. As this paper will discuss, it is similarly possible for radar to share spectrum with other systems without making the radar less effective.

There is good reason to consider spectrum sharing involving radar. Of the spectrum from 225 MHz to 3.7 GHz, roughly half (1.7 GHz) involves radar or radio-navigation infrastructure [8]. There are already proposals [9] to make some bands used by radar available for new uses in geographic regions where no radar systems are operating, while regions with radar would be "exclusion zones" that are only used for radar. Unfortunately, some of the areas with highest population density, and greatest spectrum scarcity, are likely to be within exclusion zones. There could be great value in opening up some of these exclusion zones for other uses, if it could be done without causing harmful interference to radar.

In this paper, we discuss the technical viability and policy implications of spectrum sharing between rotating radar and a 4G cellular system using OFDMA technology, both of which operate in the same area. OFDMA is used in Long Term Evolution (LTE) systems. (The underlying technical analysis can be found in [10].) Radar is considered the primary user, so the cellular system must be designed such that it never causes harmful interference to radar. We choose rotating radar operating from a fixed location, which is more conducive to sharing than other types of radar in some ways, although less in others. On the one hand, the radar system's behavior is more predictable than some other radar systems, which simplifies the sharing mechanisms. On the other hand, we assume that these are legacy systems that were not designed to operate in spectrum that is deliberately shared, whereas as future radar systems could (and should) be designed with sharing in mind.

II. SHARING MODEL

Sharing is based on the radar's rotation. From the perspective of a cellular device at a given location, rotation means that the radar's antenna gain fluctuates over time in a pattern that roughly repeats periodically. The cellular device uses dynamic power control to ensure that the interference it causes to the radar falls within the tolerable limit. Depending on the instantaneous value of antenna gain, as well as the cellular device's distance (or more precisely, path loss) to the radar, the device may be prohibited from transmitting, or allowed to transmit at full power, or allowed to transmit at a power below its maximum. Since cell radius is held constant, this reduced power has the effect of reducing cellular data rates.

Even though cell capacity fluctuates as the radar rotates, this shared spectrum can be of great use to a cellular provider. Consider the following scenario. A cellular provider serving a densely populated area where available spectrum is limited uses a combination of dedicated spectrum and spectrum shared with radar. Antennas are collocated, and cells cover roughly the same geographic areas in both the shared and dedicated bands. When capacity is sufficient, all traffic in a given cell is carried in the dedicated band. However, when instantaneous utilization exceeds the capacity of the dedicated band in that cell, some traffic is carried in the shared spectrum. The carrier may choose which traffic to shift to shared spectrum based on quality of service requirements. For example, as shown in [10] and discussed below, voice (telephone) traffic is better left in dedicated spectrum, while video streaming is better shifted to spectrum shared with radar.

III. PERFORMANCE

Even cells that are fairly close to the radar can support extensive communications on average, although with interruptions and fluctuations in data rate. To quantitatively assess the scheme, we have analyzed performance in [10] under the following specific conditions. The radar and cellular systems operate at 2.8 GHz in the same 3 MHz band. (The Federal Aviation Administration operates rotating radar in this band for air traffic control.) It is an urban area with fairly flat terrain, and this is reflected in the signal propagation assumptions [11, 12]. The radar rotates at a constant rate, and sends out pulses at a constant power. The radar's rotation period (4.7 seconds), transmit power (0.45 MW [13]), tolerable Interference-to-Noise Ratio (INR) (- 10 dB [14]), and peak antenna gain (33.5 dBi [13]), all of which are static parameters, are known to the secondary system. Background noise is -106 dBm [13]. The radar antenna is a uniformly-distributed aperture type with elevation, azimuthal 3-dB beamwidth, and front-to-back ratio of 4.7°, 1.4°, and 38 dB, respectively [13, 15]. The cellular system uses symmetric Time Division Duplex (TDD), Orthogonal Frequency Division Multiple Access (OFDMA), and 2×2 Multiple Input Multiple Output (MIMO) in both directions. At any given time, it employs the modulation (QPSK, 16QAM, or 64QAM) that maximizes data rate under current conditions. To suit an urban environment where demand is high and spectrum is limited, cell radius is 0.8 km. It is assumed that it is sufficiently unusual for a given cell's utilization to exceed capacity of its dedicated spectrum that this rarely happens in adjacent cells simultaneously, so radar is the primary source of interference rather than inter-cell interference. Mobile devices transmit at up to 23 dBm with omni-direction 0 dBi antennas, and basestations transmit at up to 46 dBm with sectorized 18 dBi antennas [16]. Background noise spectral density at a secondary receiver is -174 dBm/Hz [16].

Figure 1 shows the upstream and downstream data rates achievable in a cell averaged when over the entire rotation period of the radar, as derived in [10]. This is a worst-case scenario in which a single mobile cellular device is located at the edge of cell where path loss to the basestation is greatest, and at the point closest to the radar where interference between primary and secondary systems is greatest. Under these numerical assumptions, the radar and cellular basestation would have to be 425 km apart to avoid harmful interference to either system, i.e. to allow both the radar and cellular systems to perform as if they were in dedicated spectrum. Nevertheless, at a distance of just 40 km, the downstream rate of the cellular system is close to what could be achieved in dedicated spectrum on average, although data rate fluctuates. The impact of sharing with radar on the mean achievable upstream rate is somewhat greater, since data rate does not approach the maximum achievable until distance from the radar exceeds 200 km. Thus, this form of sharing can provide somewhat greater spectral efficiency for applications that involve greater downstream data rates. Nevertheless, the extent of communications upstream with relatively small distances to the radar is still impressive.

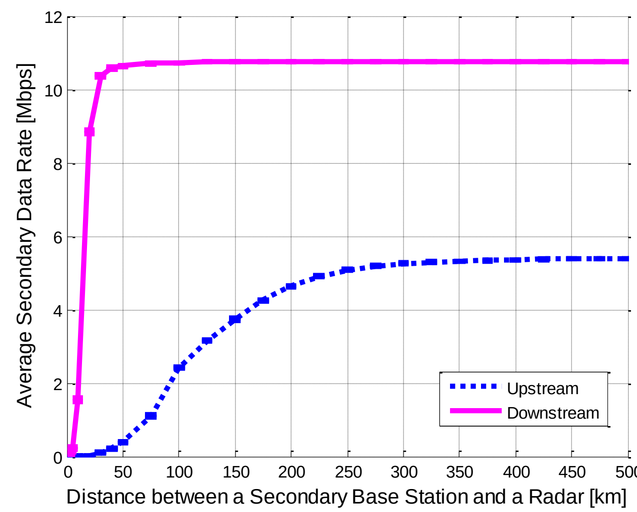

Figure 1. Mean upstream and downstream data rates of the cellular system

Whether a reasonably high but fluctuating data rate is desirable for a given packet stream depends on that quality-of-service requirements of the associated application. Indeed, whether the fluctuations are noticeable at all depends on the application as well. Consider any application that requires the transfer of a block of data which is useful only when the entire block has been received. If the transfer time equals the rotation time of the radar, or greatly exceeds it, then fluctuations will average out, and data rate as perceived by the application will equal the mean data rate. On the other hand, if transfer time is small compared to radar rotation time, then the time to transfer the file will greatly depend on when in the radar's cycle the transfer begins. Figure 2 shows the mean achievable downstream data rate for a file transfer, and the first percentile of perceived data rate[1] which represents near-worst-case performance, for files of different sizes. When transferring files of multiple MBs, performance will always be close to the average, but when transferring files of just 1 KB, an application can sometimes perceive data rate to be an order of magnitude below average. Thus, spectrum shared with radar can consistently offer perceived data rates close to those experienced in dedicated spectrum when transferring MBs of information, but not when transferring KBs of information.

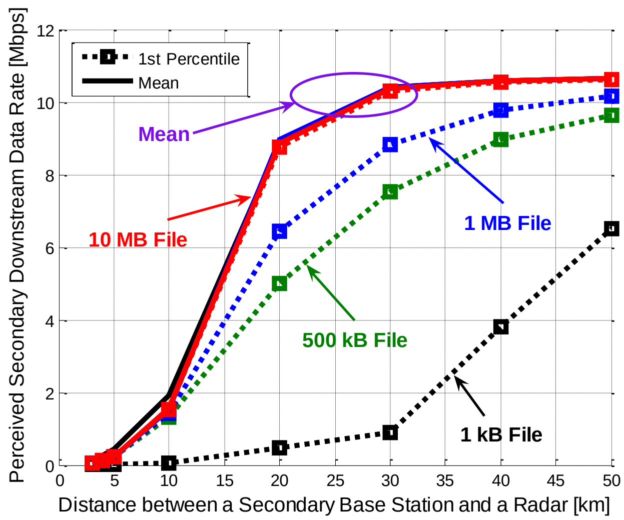

Figure 2. First Percentile and Mean Perceived Downstream Data Rate vs. Distance between Secondary Base Station and Radar.

Based on the above observation, and additional analysis shown in [10], we conclude that spectrum shared with radar is valuable for a number of common applications. For example, video streaming is a large and rapidly growing portion of Internet traffic [17]. It requires a high mean downstream data rate, but with reasonable buffering at the destination [10], the fluctuations in data rate inherent in this approach can easily be tolerated. Web browsing, peer-to-peer file sharing, meter reading, and image transfer can all be well supported in spectrum shared with radar [10]. Video, P2P, and web browsing combined are likely to constitute the vast majority of mobile Internet traffic [17]. However, any application that requires the transfer of small blocks of information in reliably short periods of time will not be well served in this spectrum. For example, interactive voice over IP (VOIP) is likely to experience unacceptable delays [10]; such traffic should be carried in dedicated spectrum.

IV. POLICY IMPLICATIONS

As shown above, it is technically possible to deploy cellular systems that share spectrum directly with rotating radar, and to do so in a way that supports high mean data rates and meets the quality-of-service needs of the majority of traffic on the Internet today without harmful interference to the radar. Thus, there are great opportunities to relieve spectrum scarcity through efficient sharing.

However, there are additional challenges to meet before realizing this potential. In general, with sharing of this kind, the gains in spectral efficiency are achieved in ways that make the primary and secondary systems more interdependent. For example, it was assumed that the designers and/or operators of the secondary system had access to some technical characteristics of the primary system, such as its transmit power, and the level of interference it could tolerate. Such sharing of information when systems are deployed requires more coordination between primary and secondary spectrum users than often occurs. Moreover, systems are not static. An upgrade to the technology in the primary system could require changes to the secondary system as well. Some changes might be handled automatically through emerging cognitive techniques, but perhaps not all. If and when they prove necessary, jointly managing upgrades to systems that are owned and operated by different organizations is more complicated.

Dynamic sharing between radar and cellular systems also creates new risks of unintended harmful interference. Such risk is particularly problematic if radar is used for safety-critical purposes, such as air traffic control. For example, there may be situations in which a system bug causes a cellular basestation to incorrectly calculate the maximum power at which it can transmit without causing harmful interference to radar. As is generally true with cognitive radio, additional means are likely to be needed to pre-certify that a new product is sufficiently safe to deploy [3], compared to devices that do not share spectrum in complex ways. In addition, in case harmful interference is observed despite a thorough precertification process, mechanisms will be needed with which the secondary system can be forced to reconfigure or discontinue operation in the shared band. This may need to occur much more quickly than is typically possible through complaints to the regulator.

If all primary and secondary systems were under the same administrative control, coordination would be relatively easy. For example, this might occur if the Department of Defense deployed both radar and cellular in the same spectrum for its own use. If all radar systems are under the same administrative control, then giving this primary user authority to prevent dangerous technology from being deployed in secondary systems operating in the band, and authority to require secondary systems to terminate operations in the event of harmful interference, may solve many problems. This would occur if sharing occurred under the rules of real-time secondary markets [18]. However, in the case where multiple entities have deployed radar systems, and multiple entities have deployed cells, all within the same general region, a new form of governance will be needed that has both the capability and authority to address complex interference issues.

[1] Perceived data rate = (total file length) / [(the time when the file completes transmission) – (the time the file is first available for transmission, regardless of when transmission can actually begin)].

Finally, note that in the scenario addressed in this paper, a wireless Internet service provider should treat traffic differently depending on the associated application, e.g. transmitting video-on-demand over shared spectrum and VOIP over dedicated spectrum. This observation deserves consideration should network neutrality regulations be applied to wireless networks [19], although there are certainly traffic control approaches that would achieve this result and that are consistent with reasonable network neutrality principles [20].

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