Analysis and Simulation of Adjacent Service Interference to Vehicle-Equipped Satellite Digital Radio Receivers From Cellular Mobile Terminals

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Abstract— This paper provides detailed analysis and simulation for exploring the impact of out-of-band emissions (OOBE) of adjacent wireless services to the Sirius XM digital satellite radio service. Based on an extensive analysis of interference from vehicles with mobile cellular users in realistic roadway conditions, we propose proper methods for determining out of band emission spectral masks that should be used by new WCS cellular subscriber transmitters in the 2.3 GHz band. Analysis for roadway and propagation conditions in various US cities resulted in the suggested masks. This work presents the first simulation of its kind and offers approaches that federal regulators may use to determine spectral masks that allow harmonious co-existence of existing mobile radio listeners with new cellular and fixed broadband mobile services in adjacent spectrum bands.

II. THE SIRIUS XM SATELLITE BROADCAST SYSTEM (SDARS) AND WCS

The Sirius XM satellite radio system is a broadcast system designed for simplex transmissions (receive-only) [1]. The inability to use feedback for broadcasting stations in turn requires them to have more protection from interference than other systems that are dynamically adjustable. Broadcasters are licensed based upon their fixed installation and placement of transmitters, and are given strict licensing requirements with their spectrum allocation. Because of the fixed and rigid requirements of transmitter power levels, antenna heights, and placements, broadcast systems are operated in a "noise-limited" regime, where the coverage provided by the broadcaster is limited by the signal power it is able to propagate to the listener, and the listener’s noise level at her receiver. Cellular systems, on the other hand, are operated in a noise-limited regime, and are relatively unrestricted by their license from adding new base stations and adding more subscribers over time within a geographic area, as customers are added to the network. Broadcast systems are designed to maximize coverage from just one or a few transmitters, although repeaters may be used to augment coverage problems. For Sirius XM, hundreds of ground based repeaters are located throughout the US to provide coverage holes caused by shadowing of the satellite signal due to buildings and foliage, although repeaters cover less than 1% of the CONUS coverage region. Achieving high broadcast quality of service targets required the use of dual path satellite diversity broadcasting, and antenna beam shaping to increase the link margin in areas with lower elevation angles to the satellites.

Since broadcast systems use one-way transmission systems, they do not introduce additional interference as listeners are added. This is because all new listeners are simply receive-only – they do not transmit, and thus do not add to the spectral interference level of the system. The fact that broadcast systems do not produce interference as listeners are added is in contrast to wireless mobile systems which...
continually increase their total interference power levels and out of band emissions (OOBE) as more mobile subscribers are added to the network. Degradation of the link margin due to OOBE interference implies that there is less excess power on the radio link to protect against fading and interference. In the event that the fading or interference losses exceed the link margin, the receiver’s reception will fail.

Modulation techniques of the Sirius XM satellites, types of satellites used, apportionment of content on the satellite uplink, and use of redundancy are slightly different in the legacy XM and Sirius systems, yet both systems provide extremely similar signal level performance on earth, as both satellite systems were designed and deployed using state-of-the-art satellite engineering concepts under similar FCC rules [1]. SDARS is a mobile service that requires an omni-directional reception capability on a vehicle installation. Satellite signal power levels are weak when compared to modern terrestrial mobile and fixed wireless systems. For example, the Sirius satellite power level received in Miami is -101 dBm, and the thermal noise level is -113 dBm/4 MHz, yielding 12 dB signal to noise ratio without WCS interferers.

The WCS system is not yet deployed, but will most likely be a cellular-like broadband wireless system to provide mobile and fixed broadband service using a cellular architecture. While the Sirius XM broadcast system provides signal levels that are no greater than -94 or -95 dBm over a 4 MHz bandwidth on earth, cellular systems typically operate at minimum useable signal levels of -80 dBm or greater over a 4 MHz bandwidth, certainly with much higher link margins than satellite systems, as they are pre-designed to anticipate future self-interference from more users over time. Typically, cellular systems operate at 20 dB to 30 dB above the thermal noise floor, and use adaptive modulation on both the forward and reverse link for agility in signaling data rates to adapt to charging interference and coverage levels.

Regardless of the size of the guard band between the SDARS spectrum and the WCS emissions, it is the power level of out-of-band-interference allowed to come from WCS subscriber units that will dictate the level of degradation to the SDARS listener. The current FCC rules call for an OOBE mask defined by $110 + 10 \log P$ for mobile transmitters. The OOBE formula requires that the WCS subscriber out-of-band emissions within the 1st MHz of the SDARS band directly adjacent to the upper or lower WCS blocks shall not exceed -110 dBW per MHz. These FCC rules were based on the requirement that WCS protect SDARS such that any out of band interference would only be allowed to raise the SDARS noise floor by 1 dB.

The WCS transmitters also have the ability to overload the SDARS receivers, such that there are two independent mechanisms from the adjacent band WCS transmitters – OOBE that creates a linear increase in the noise floor due, and desensitization due to non-linear signal overload and intermodulation products from nearby WCS mobile transmitters that overtake the receiver circuitry at satellite radio receivers. The only way to fully understand the impact and sensitivities of communication system performance is through complex Monte Carlo simulation, as described in the following.

III. A SIMULATOR FOR STUDYING WCS OUT-OF-BAND INTERFERENCE IMPACT ON SDARS

To determine realistic interference levels and the resulting degradation to satellite receivers, we developed an extensive simulation environment based on Matlab. The simulator allows an engineer to input important propagation parameters, traffic parameters, and transmitter and receiver parameters to determine real-world affects and resulting SDARS outages caused by WCS mobile stations that radiate out-of-band interference. The use of simulation is arguably the only method for determining the impact of OOBE on the listening public in realistic environments. The simulator considers the random location of WCS mobile stations and SDARS listeners, the likelihood of whether the WCS mobile stations are transmitting and if the SDARS receivers are turned on, the duty cycle of a transmitting WCS subscriber, whether the WCS subscribers are from the different WCS spectrum blocks, whether the WCS system is using mobile station power control, and the particular transmission power and power control level for each transmitting WCS subscriber station. The simulator also allows the user to specify different vehicle-to-vehicle path loss models that govern the propagation of out-of-band interference from the WCS mobile stations to each of the Sirius XM receivers, and different user-specified masks, are used on each of the WCS mobile transmitters. This allows us to compare the impact of WCS OOBE on SDARS listeners. The simulator also uses the satellite look-angle data and link margin data to determine accurate outage probabilities for a wide range of different latitudes and longitudes.

IV. HIGHWAY TRAFFIC, ROADWAY, AND SUBSCRIBER ADOPTION RATE MODELS

The simulator must properly model the impact of adjacent service out-of-band interference from mobile WCS users, and the resulting degradation to mobile SDARS listeners, thus it is necessary to first consider a realistic highway environment. Our simulator allows the engineer to enter roadway length (in miles), the number of highway lanes on the road, the average speed of each vehicle, and the traffic volume of vehicular traffic as measured in cars per hour. Our simulator then generates the random locations of specific vehicles traveling throughout a highway. We assume interstate highways and freeways have lane widths of 3.5 meters in the simulation, which is standard for roadway construction.

In the simulation, we assume that each lane of the highway has a uniform distribution of highway traffic, so that users may be randomly located in any of the highway lanes, as found in typical urban and suburban highways. The selection of roadway length is a variable parameter and can be adjusted to describe the roadway being modeled. For the simulations, we chose five typical US cities with varying latitudes and
longitudes (New York City, Jackson, MS, Denver, CO, Miami, FL and Charlotte, NC), and selected popular highways within each of those cities where Sirius XM relies upon satellite coverage, and not its terrestrial repeaters. Each of the selected road segments has a corresponding daily traffic volume (in cars per day) distributed over a 24 hour period. For the simulator, we assume that 60% of the daily traffic flow occurs during the 4 peak hours (two peak morning hours of 7 - 9 am and two peak evening hours of 4 - 6 pm) during a day, and determine a typical rush hour traffic volume (in cars per hour) by multiplying the overall daily volume by 60%, and then dividing by 4.

At any given time during any one of the four peak travel hours, the gross number of vehicles is determined by multiplying the traffic volume by the roadway length, and then dividing by the speed of travel. The total number of vehicles on the roadway segment, a certain proportion will be satellite radio subscribers and another portion will be WCS service subscribers. The simulator provides inputs to specify the user density of SDARS listeners and WCS users. These data are entered as a customer penetration rate, in terms of percentage of total vehicles, and dictates the user density of both WCS users and SDARS listeners on the simulated highway. For the work presented here, a satellite radio penetration rate of 34% is used. WCS market penetration was estimated to be a moderate 5%. It is assumed that only half of those WCS transmitters interfere with one of the satellite radio systems, and their OOBE is adjusted properly to account for their frequency separation from the satellite radio band. Also, random duty cycle assignment is made on the WCS transmitters, and as a result, their OOBE was scaled to account for their duty cycle and the power control. Vehicle-to-vehicle signal propagation was modeled using publicly available measurement data. Based on published papers from the Netherlands, Carnegie Mellon University, and the Intelligent Vehicle Highway Systems community, we find that many measurements and models have been proposed for vehicle-to-vehicle communication systems in the 900 MHz to 6 GHz range [2], [3], [4], [5], [6], [7]. These models in the literature, and the models used in the simulation, follow the form given by eqn. 4.69a in Rappaport’s 2002 Wireless Communications text as

\[
PL \ (dB) = [\text{Free Space Loss at } 1m] + 10*n \log (d) + X_c \ (1)
\]

where n is the path lost exponent and Xc is a mean diffraction loss parameter and Gaussian distributed in dB. Carnegie Mellon proposed a path loss model having a log-distance path loss exponent of n=1.8, and a log-normal shadowing of 5.5 dB. Other propagation models propose a free space path loss model of n=1.8 to n= 2.0, and one study found that n=3.1 but indicated the high value of n is likely due to a single attenuation factor related to car body loss.

Based on the above cited data, as well as measured results provided by Sirius XM and WCS operators in SWRI, WCS Old, and WCS New, we propose several different vehicle-to-vehicle propagation path loss models [8], [9], [10]. We employ the concept of a mean attenuation factor, a diffraction parameter that models the cumulative effects of car body loss, human body loss, and blockage between vehicles. Based on reported measurements, we assume loss factors of 10 dB and 16 dB, and consider path loss exponents of n=2.0 and 2.18.

We also assume log-normal shadowing due to variations in the channel, and consider standard deviations of the shadowing to be 0 dB, 2 dB, and 4 dB. We note that the loss factors add attenuation above the distant-dependent path loss model, and the log-normal shadowing allows our simulator to generate realistic random effects that will impact interference levels received at SDARS receivers. We use Xc to represent a random shadowing loss that is assigned a mean value of either 10 dB or 16 dB, and is log-normally distributed (normal in dB), and the free space loss at 1 m is 40 dB. In our simulations, Xc is a Gaussian random variable having values in dB. The simulator allows the user to consider either a free space path loss exponent value of n≈2.0, as well as a path loss exponent value of n≈2.18. Standard deviations for the log-normal shadowing component are selected as either 0 dB, 2 dB, or 4 dB for the path loss.

The simulation applies the path loss model to the all of WCS transmitters and generates a random path loss value for every WCS transmitter. Then, the simulator computes the distance between every WCS vehicle and SDARS vehicles, and computes the resulting received interference power at each SDARS receiver, based on the particular FCC interference protection mask that is specified in the simulator. We make the fair assumption that each WCS transmitter is independent from one another, or at least uncorrelated and of zero mean, such that the interference powers from multiple WCS transmitters are added in a linear fashion at a particular SDARS receiver. Based upon the simulated levels of interference at each SDARS receiver over a large number of iterations, the simulator produces statistics that determine SDARS listener quality degradation based on outages, as well as the satellite link margin reduction due to WCS interference.

For the simulation results presented here, we assume that active WCS transmitters are proportioned such that 64% of the WCS transmitters are transmitting with full subscriber transmit power levels, 23% of the WCS transmitters are transmitting at 6 dB below their maximum power level, and 13% of the WCS transmitters are transmitting at 12 dB below their maximum power level. The step of implementing the effect of power control is performed on the eligible active WCS transmitters are proportioned such that 64% of the transmitters are transmitting with full subscriber power levels, 23% of the transmitters are transmitting at 6 dB below their maximum power level, and 13% of the transmitters are transmitting at 12 dB below their maximum power level. The step of implementing the effect of power control is performed on the eligible active WCS transmitters that remain, after “turning off” the transmitters that are inactive based on the specified activity factor.

The simulator allows for the user to specify attenuation values that are applied to the WCS transmitter spectrum masks, in order to take into account the FCC’s proposed rules that require WCS interference components at SDARS receivers to produce less interference as the frequency
separation increases. The model used in the simulator allows the user to select different levels of attenuation to be applied to the WCS transmitters at different frequencies away from the SDARS spectrum.

For example, to study the FCC's proposed rules, the simulator must implement the $55 + 10 \log P$ spectral mask for a 0.25W WCS subscriber transmitter using a 2.5 MHz channel in the D block. To do this, we compute the attenuation required by the mobile station as $55 + 10 \log (0.25W)$ dB. This equates to 55 dB - 6 dB = 49 dB of attenuation applied to all D block WCS transmitters. For all WCS transmitters assigned to be in the first adjacent channel (e.g. the A-upper block), the simulator implements 61 - 6, or 55 dB of attenuation level to implement the FCC's proposed $61 + 10 \log P$ OOB mask for the case of 0.25W transmitters. The simulator applies $67 - 6 = 61$ dB of attenuation for the B-upper block WCS transmitters in order to implement the FCC's proposed $67 + 10 \log P$ mask with 0.25 W transmitters. If all WCS carriers use subscriber equipment that have identical spectral mask characteristics, then it is reasonable to assume that identical equipment in the WCS upper band (A block) would cause less interference into the SDARS band as compared to D block transmitters, since the spectral emissions from WCS subscribers are further attenuated.

As discussed earlier, the simulator computes the distances between all WCS and SDARS vehicles, and then calculates the random path loss for WCS signals at each SDARS receiver based on a distant-dependent path loss model with a mean diffraction parameter. The cumulative interference at each SDARS satellite receiver is then calculated by summing up interference levels from all WCS transmitters. For each iteration, the simulator computes and stores the aggregate power from each of the WCS transmitters as seen at each SDARS receiver, as well as the aggregate total WCS OOB power which appears as interference. The overall statistics of WCS interference power levels are computed over many iterations. The simulator uses the satellite look angles, antenna patterns, and link margins in order to determine the signal levels at different locations on earth. The simulator incorporates the actual designs employed by Sirius XM to exceed 99% availability under worst case Extended Empirical Roadside Shadowing (EERS) model assumptions [11]

V. SIMULATION RESULTS

As described in Section 4, the power control "bands" used in the simulation are based on a statistical distribution of WCS vehicle location in a base station coverage area. The power control levels are settable and distributed randomly to the WCS users, in proportion to the cellular coverage zones, and the simulations have been set to 0 dB (max power), -6 dB, and -12 dB from full power. Out of the total pool of WCS transmitters on the roadway segment, a portion is declared inactive due to the WCS activity factor of only 13% being on. Specifically for the results presented here, the WCS users are assigned power control values in the following way: 63.2% at full power, 23.4% backed off by 6 dB, and 13.4% backed off 12 dB from full power. All the WCS transmitters, active and inactive, then receive a random power level assignment for each iteration.

The received power at the SDARS receiver is calculated by subtracting the total path loss, per the vehicle-to-vehicle propagation models in Section 4 from the transmitted power. Included in the total path loss is the statistical blockage factor with a settable mean level in dB, and a standard deviation settable to between 0-4 dB. The mean for the blockage is assumed to be a minimum of 10 dB, and maximum 16 dB. This factor is randomly assigned for each individual calculation. The engineer can vary the path loss parameters to assess performance using different assumptions.

Traffic volume, speed and roadway characteristics determine the total number of vehicles on the simulated roadway segment at any time during the peak rush hour. A subset of the total vehicles will be satellite radio subscribers or WCS service subscribers. The number of subscribers to both services depends on how widely consumers adopt the respective services. This adoption factor is referred to as the penetration rate. For the satellite radio, it is likely that the penetration rate will grow to 34% of vehicles in the next few years. The WCS penetration rate is more difficult to estimate as there is little or no current service available. Therefore a penetration rate of 5% was assumed for the simulations. Penetration rates for both services are settable parameters in the model, and can be adjusted for future growth. As both services grow, the likelihood of their subscribers sharing the road in close proximity will increase. The final step in conducting this analysis is to evaluate the impact of interference received at the satellite radio in terms of link quality and signal availability.

This relationship between link margin and elevation angle can be statistically estimated using a technique called the EERS model [11]. This model computes the outage probability for different combinations of elevation angle and link margin. This produces a quality of service level to compare performance with and without interference. Similarly, we also find the number of satellite radio users that experience link margin degradations that exceed of 1, 2 or 3dB or more.

We ran simulations for five major US cities: Charlotte, NC, Miami, FL, New York/NJ Turnpike, Jackson, MS and Denver, CO. As example, we simulated rush hour traffic on a 7.5 mile portion of Highway 836, southwest of Miami FL. Table 1 shows the traffic parameters for Miami which were applied to the simulator. Using the traffic volume calculation techniques, we calculate a peak hourly volume of 13795 vehicles on the highway. Using the simulator, with the satellite link parameters shown in Table 2, we found that the Baseline availability is 99.78% for a 99% worst case availability criterion. In other words, without WCS interference, only 0.22% of the SDARS receivers in the Miami will experience an outage more than 1% of the time.
A total of 7,251,200 vehicle locations were simulated over 100 iterations, where each iteration was conducted under the assumption that 103 WCS transmitters and 704 SDARS receivers were located nearby. The satellite geometry, link performance and overall QoS for Miami are shown in Table 2. Table 3 shows the simulation results for two different propagation models. One model assumes a free space path loss exponent of \( n = 2 \), and a 10 dB attenuation factor, with a shadowing standard deviation of 4 dB, whereas another model assumes a path loss exponent of \( n = 2.18 \), a 16 dB attenuation factor, and a 4 dB standard deviation.

**VI. CONCLUSION**

This paper has analyzed potential interference to satellite receivers by making reasonable engineering judgments in order to deduce the levels of OOB E that would be seen from adjacent service WCS subscribers in the SDARS band. In doing work, we sought to determine reasonable guidelines from which suitable spectrum masks could be developed. The simulations presented here show how many WCS transmitters leads to an increase in SDARS receiver noise floor. The simulation statistics provide insights into the exact degree of this phenomenon by counting the noise floor levels for each of the SDARS receivers as the noise floors are raised by 1, 2, and 3 dB or more.

**REFERENCES**


