PROPAGATION EFFECTS AND SATELLITE RADIO DESIGN

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ABSTRACT

Sirius Satellite Radio is providing CD-quality satellite audio broadcasts at 2.3 GHz to vehicles traveling anywhere in the continental US. The most effective design decisions applied to overcome signal fading from multipath, roadside tree shadowing, and blockage by buildings are discussed by presenting propagation measurement results. Significant system features include very high elevation angles due to a non-geostationary and highly eccentric orbit, time diversity, satellite diversity and coding/interleaving diversity. The measurements in forested areas are compared to the ITU satellite mobile propagation model and it is found that the model significantly over-predicts fading for the high elevation angle case.

INTRODUCTION

Propagation studies for mobile satellite services performed over the last 20 years in Australia, Canada, Europe, Japan, and the United States, summarized in [1], have documented the difficulty of achieving high-probability coverage between a satellite and a car moving along a road. It was soon discovered that at the frequencies under consideration for future systems, reaching from 800 MHz to a few GHz, most of the significant problems arise in the close vicinity of the mobile terminal. This is in contrast to terrestrial wireless links, where propagation effects are generated by the topographical characteristics of the entire coverage area surrounding the base-station and mobile terminal. The cause for this difference, in addition to the path geometry, is also the available fade margin. Terrestrial systems can call on a deep range of power to maintain a connection between a base-station and a mobile terminal over a rather short distance and within a small coverage area. Satellites, on the other hand, have to provide service across a large distance, over continent-sized areas, and with power limited by the complexities and cost of having to generate it in orbit. Satellite propagation effects, therefore, are primarily due to the attenuation caused by roadside obstacles in the line-of-sight path. Fades can either be generated by absorption or by scattering. To a lesser degree, and especially when compared to the terrestrial case, the spread of signal arrival times can cause problems to wideband satellite systems. Delay spread exists because scattered multipath components travel over different distances before arriving at the receiver.

Satellite systems designers are charged with the task of overcoming the limitations imposed by the propagation conditions mentioned above and thus have to understand the characteristics of the signals in space, time, and frequency in order to select optimal design solutions. That task is somewhat simplified in the case at hand, satellite broadcast service, because the user signals only travel from space to ground. Complications found in bi-directional communications services, such as the length of the absolute path delay, interference from other users' terminal transmissions, most networking issues, etc. are avoided. We can therefore restate the problem as the task to provide high-availability, high-quality, multi-channel and economical radio services to land-mobile vehicles at a frequency near 2.3 GHz anywhere in the continental United States in the face of signal fading caused by absorption, reflection or diffraction from any possible obstacle that obscures the line-of-sight path to the vehicle or is located close to the vehicle. In addition, the service has to have the same level of end-user simplicity as a conventional car radio.

The paper will report on results of a propagation measurement campaign carried out in 10 States, comprised of about 60 hours of data in 9 land use categories. Examples of predicted performance with and without satellite diversity and delay will be shown. The sensitivity of the results to the delay time will be presented. Cumulative distributions of the relative signal level will be shown in some of the environments. The ITU roadside tree shadowing predictions will be assessed.

PROPAGATION EFFECTS FOR SATELLITE RADIO

To appreciate the design decisions, it may help to imagine the signal strength as a surface with a height proportional to signal strength at each possible receiver position. The reduction to two dimensions can be made because cars travel on a surface (mostly a horizontal one) with the antenna height fixed above the road. If the satellite is not moving with respect to the ground, the interplay of the direct wave, which may or not be attenuated by roadside vegetation or by a solid obstacle, and any other wave generated by nearby illuminated objects sets up a fixed standing wave pattern with crests and valleys separated by as little as half a wavelength at the RF signal frequency. If the satellite moves, the surface will slowly change as the variation in the path geometry changes the relative phases of all the interfering wave components, just as the surface would change if any of the obstacles, such as trees in the wind or other nearby cars, were moving. As the vehicle-borne receiving antenna moves through this field, it samples the signal strength that exists at each position along its path. Variations due to multipath interference are of wavelength scale and those due to shadowing by trees and blockage by buildings are proportional to the size of the obstacle. Converted to variations in time by the speed of the car, those due to multipath may last for fractions of a second while those due to a change in the line-of-sight status to *not clear* may last many seconds. Examples of signal levels due to shadowing by roadside trees and blockage by urban core buildings are depicted in Figs. 1 and 2. Note that the time scales cover half a minute and about half an hour, respectively.

The specific characteristics of the satellite signal strength depend on the vehicle's speed and the morphology of the environment where it is located. The probability of having a blocked path in North America is greatest in urban areas, with extreme conditions in the canyons created by tall buildings in central business districts. Commercial/industrial zones and typically low-rise residential districts present fewer blockages. In residential areas, however, signal shadowing by trees with overhanging foliage is experienced often. Roadside tree effects are also dominant along many traffic arteries through agricultural or forest zones with occasional short blockage caused by overpasses. The probability of having a clear, shadowed or blocked path has been quantified as a function of the environment and the elevation angle by optical and other means. As expected, the probability of having a clear path from a satellite while moving along a road increases with elevation angle in most environments. Exceptions are specific locations such as tunnels, parking garages and tree-lined streets with overhanging foliage.

SIRIUS SATELLITE RADIO PROPAGATION MITIGATION DESIGN

High Elevation Angles

The Sirius satellite radio systems design represents a number of significant choices in response to the challenges outlined above. Its most effective constituents discussed here include (1) high elevation angles, (2) satellite diversity, and (3) time diversity. High elevation angles are achieved over the entire continental US, including the northern states more difficult to serve from geostationary orbit, by orbiting three satellites in one Molnya Orbit, with two of the satellites visible and providing service at any time with varying degree of angular separation from each other. Figure 3 demonstrates the high service elevation angles achieved by the Sirius constellation at Detroit, Michigan. Elevation angles for other locations in the USA are summarized in Table 1, which for comparison also includes the elevation angles to the two geostationary satellites of the XM Radio constellation.

Table 1. Sirius elevation angles, in degrees, at locations throughout the USA

	Sirius Satellite Radio				XM Radio	
	Minimum High Sat	Average High Sat	Minimum Low Sat	Average Low Sat	XM-1	XM-2
Detroit, MI	64	71	24	61	41	31
Seattle, WA	64	68	13	52	25	35
San Diego, CA	52	64	23	55	39	52
Houston, TX	52	69	41	58	53	49
Miami, FL	46	66	30	51	59	41
Bangor, ME	61	65	13	53	36	21
Denver, CO	62	71	29	63	40	43

For Seattle, WA, for instance, the lower of the two visible Sirius satellites is below 20° for 5% of the time, but the higher one at the same time is always above 64°.

Satellite and Time Diversity

As the two visible Sirius satellites move along a figure-eight track (see Fig. 4), they transmit the same signal, but with a few seconds of time shift relative to each other. This provides simultaneous satellite and time diversity. The relative motion of the satellites modulates the effectiveness of satellite diversity, but the time diversity is constant. The combined diversity improvement is demonstrated in Figs. 5 to 8 for an 80-minute test near Pasadena, CA with a route map, satellite azimuth angles, CDFs, and signal level time series. In Fig. 8, each satellite is seen to fade often, but when the signals are diversity-combined (the lowest trace), almost all the fades disappear. Here a delay time of about 3.1s was used. When varying the delay from 0.8s to 100s, most of the gain is achieved within a few seconds, after which the fades become decorrelated. In the cumulative distribution functions (CDFs) plotted in Fig. 7, the upper three curves are for the two satellite signals and the zero delay combination for the satellite diversity effect only. The satellite azimuth angles in this case are nearly opposing and only minimal space diversity is achieved because with this geometry overpasses along the E-W route can block both satellites simultaneously. The added effect of time diversity is dramatic, however. It reduces the fade probability to below the receiver threshold by a factor of 10 from 1% to 0.1%.

COMPARISON TO ITU MODEL

About 10% of the propagation data were taken in areas classified as *Forest* and the measured CDFs are compared to the ITU Roadside Shadowing Model [2] in Figure 9. The ITU model, depicted in the upper two curves for the maximum and minimum elevation angles of the measurement, over-predicts fading, possibly because it was developed based on a geometry in which the satellite is at right angles to the vehicle heading. Also, relatively few high elevation data were available to develop the model. The over-prediction holds even when the model fades at 80° elevation are arbitrarily reduced by 75%, although in that case the fit is improved.

CONCLUSION

The shortest fades, such as those due to multipath interference, can be overcome by code diversity. Longer fades are mitigated most effectively by time diversity. Such fades might be experienced, for instance, when driving under an overpass or along tree-lined roads. Because of the favorable elevation angles of the Sirius constellation, only the most severely blocked urban areas will need terrestrial repeaters to fill in the service areas.

REFERENCES

[1] Goldhirsh, J. and W.J. Vogel, 1998, Handbook of Propagation Effects for Vehicular and Personal Mobile Satellite Systems; Overview of Experimental and Modeling Results, http://www.utexas.edu/research/mopro/

[2] ITU, 1999, Recommendation ITU-R P.681-4, "Propagation Data Required for the Design of Earth-Space Land Mobile Telecommunication Systems," http://www.itu.int/home/index.html

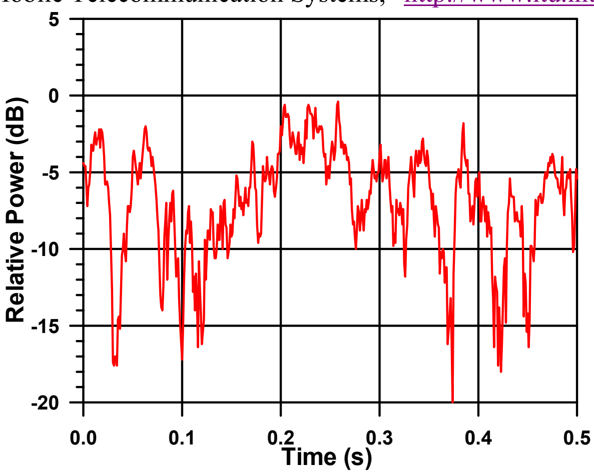

Fig. 1. Example of roadside tree shadowing

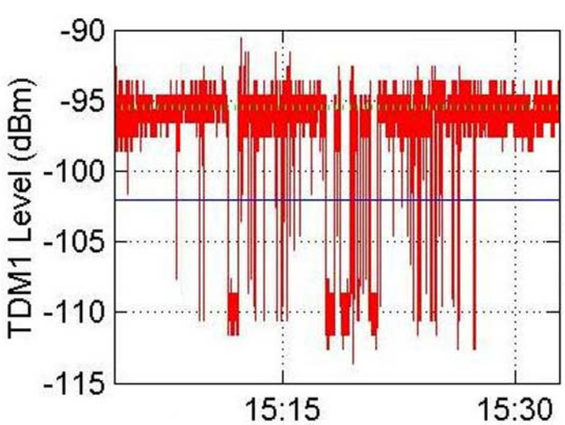

Fig. 2. Time series of urban blockage (hh:mm)

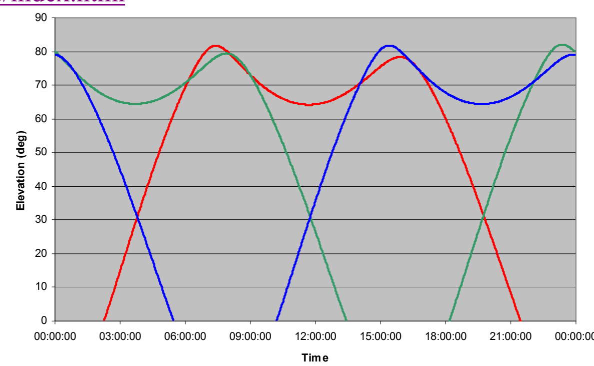

Fig. 3. Sirius elevation angles in Detroit, MI. Each color represents one satellite (R=S1, G=S2, G=S3).

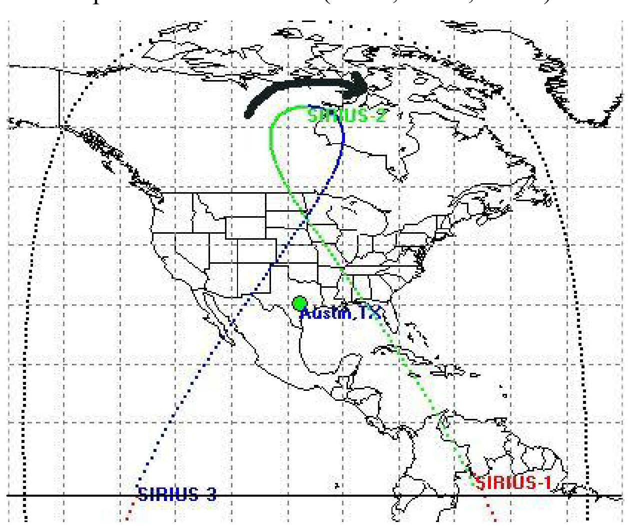

Fig. 4. Sirius ground tracks for 8 hours

Fig. 5. Test route in Pasadena, CA (80 minutes)

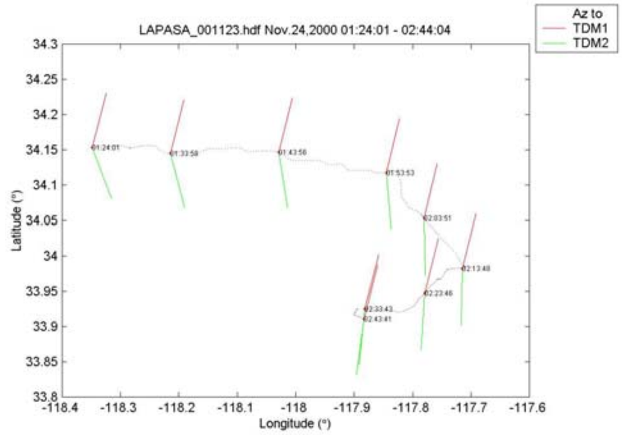

Fig. 6. Azimuth angles on route in Pasadena, CA

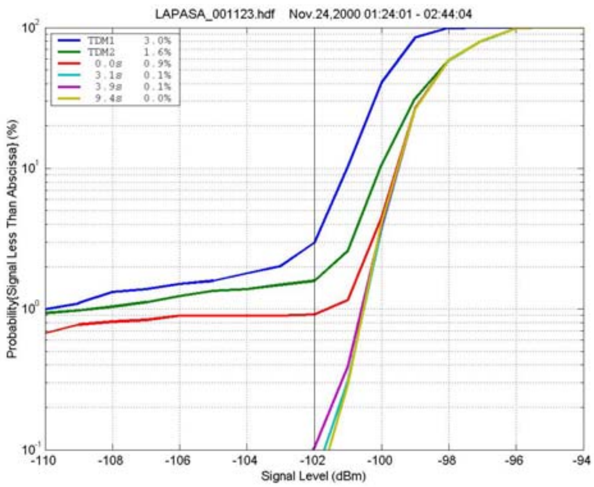

Fig. 7. CDFs for Pasadena, CA test route

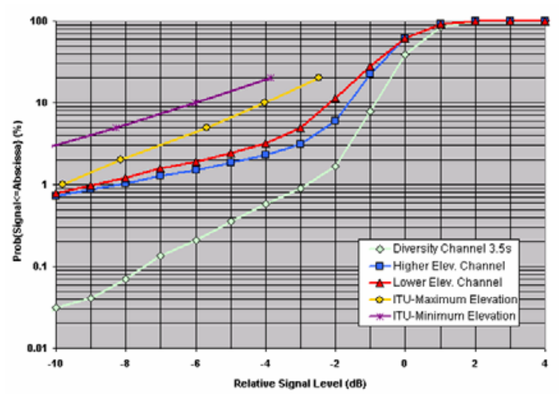

Fig. 9. The ITU model over-predicts fading at high elevation in forest environment

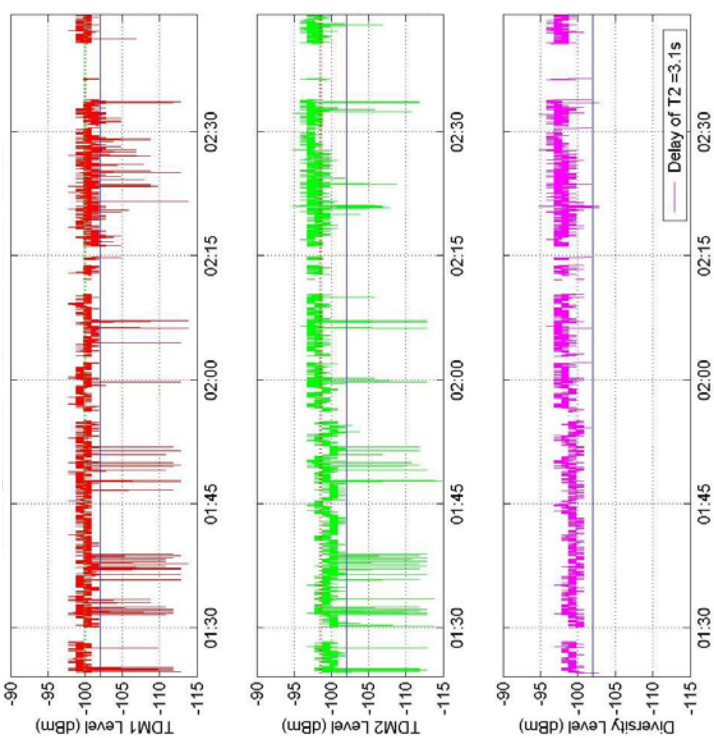

Fig. 8. Time series for Pasadena, CA test route demonstrating that by using diversity fade mitigation most fade events are eliminated