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Providing Narrowband IoT Coverage with Low Earth Orbit Satellites

Kenneth M. O'Hara and Gregory J. Skidmore
Remcom Inc., State College, Pa.

This article describes the modeling of a SATCOM link, specifically the use case of using a satellite overlay to extend service continuity to IoT devices in a poorly covered rural area.

Non-terrestrial wireless networks (e.g., satellite constellations or high altitude platforms) have unique advantages—wide area service coverage and long-term reliability—which make them important components in the heterogeneous 5G global system of networks. Non-terrestrial networks (NTN) will likely play a critical role providing service to locations not covered by terrestrial 5G networks, such as rural and remote areas, moving platforms and disaster-stricken zones. One use case for NTNs is providing service continuity for machine-to-machine (M2M) or IoT devices as they move out of 5G terrestrial network coverage.[1] This is particularly important for M2M/IoT devices which provide critical communications (e.g., applications in eHealth or vital asset tracking).

NARROWBAND IoT

Requirements for M2M and IoT communications can differ significantly from those for voice and data streaming: data throughputs are typically much lower. A prominent feature of M2M and IoT devices is a requirement for low-power consumption. Fortunately, these aspects of M2M/IoT communications can be simultaneously satisfied using a narrow bandwidth, low-power, wide area network (WAN). Narrowband IoT (NB-IoT) is an example of one such network standard, incorporated into 3GPP release 13 and further enhanced in releases 15 and 16 to ensure the ability to operate within a 5G ecosystem. The low signal power of these devices is accommodated through the lower bandwidth of the NB-IoT standard, which helps to reduce RF noise. Fortunately, this narrow bandwidth requirement is consistent with the low data rates acceptable for these communications.

NB-IoT is based on a simplified LTE standard with a maximum bandwidth of 200 kHz, transmitted either in dedicated bands, in-band within LTE or 5G NR carriers or within their guard bands. The peak downlink and uplink rates using the full bandwidth are 250 kbps; systems with lower data throughput can use individual subcarriers.

LEO SATELLITES

While satellite networks have the advantages of wide service coverage and reliability, their communication links unavoidably suffer from comparatively large latencies and propagation losses. To minimize both, satellite constellations in low Earth orbit (LEO) can be used to communicate with NB-IoT devices on the ground (see ***Figure 1***). For example, the round-trip latency for a LEO satellite orbiting at 1000 km is less than 10 ms when the satellite is directly overhead. The free space propagation path loss, FSPL, is given by the Friis transmission formula:

$$\mathrm{FSPL(dB)} = 20\log\left(\frac{4\pi d}{\lambda}\right) \qquad (1)$$

where d is the distance and λ the wavelength. The FSPL is the dominant contributor to loss in the satellite link budget and is minimized by the smaller propagation distances associated with a LEO satellite and using larger wavelengths. For λ = 14 cm (a 2.1 GHz carrier) and d = 1000 km, the FSPL = 159 dB for a satellite directly overhead (elevation = 90 degrees). The propagation path increases for lower elevation angles due to the longer slant range to the satellite associated with line-of-sight (LOS) propagation with refraction and absorption in the Earth's atmosphere. Using L- and S-Band carriers, rather than higher frequencies, keeps the atmospheric absorption relatively small.

LEO satellites have the disadvantage of the communications channel being complicated by relatively large Doppler shifts. To maintain its orbit, a LEO satellite at an altitude of 1000 km must have a velocity, v, of 7.4 km/s. The Doppler shift due to this motion is given by:

$$\Delta f = \left(\frac{1}{2\pi}\right)\vec{k}\cdot\vec{v} \qquad (2)$$

where $\vec{k}$ is the wave vector of the radio signal at the position of the satellite. The wave vector has a magnitude of $k = 2\pi/\lambda$.

For a LEO satellite in polar orbit, ***Figure 2a*** shows the Doppler shift as a function of time for downlink and uplink carrier frequencies near 2 GHz, where t = 0 is the instant when the satellite passes directly overhead. The corresponding elevation angles are shown on the upper axis. The uplink (UL) (1.7 GHz) and downlink (DL) (2.1 GHz) signals experience different shifts due to their different wavelengths. To accurately account for the direction of the signal wavevector $\vec{k}$ at the location of the satellite, an in-house ground-to-satellite propagation model based on ITU-R P.676-11[2] and ITU-R P.834-8[3] has been used to account for the refraction in the atmosphere (which bends the radio wave toward the surface of Earth) compared to direct LOS propagation. The time rate of change of the Doppler shift is shown in ***Figure 2b***. To avoid inter-band interference, the common mode component of the shift must be dynamically compensated for by the satellite, with the remaining differential shift across a coverage area being compensated for by the user equipment (UE).[4]

Other factors which affect satellite-to-ground link budgets include rain fading, ionospheric and tropospheric scintillation, terrain masking, foliage attenuation and multipath effects. For L- and S-Band carriers, typically employed in NB-IoT communications, rain fading and tropospheric scintillation effects are relatively small.[5-6] Ionospheric scintillation, on the other hand, can cause deep time-dependent fades during the hours following sunset for UEs located within 20 degrees of the equator or at high latitudes near the poles.[7] Link budgets for UEs located within these regions can require margins of at least 25 dB, especially during periods of high solar activity. At other latitudes, ionospheric scintillation can typically be neglected. To account for terrain masking, foliage attenuation and multipath effects, especially in a well characterized scene, ray tracing techniques can be employed.

MODELING SATELLITE COVERAGE TO RURAL AREAS

We now consider the use case of extending service continuity to mobile NB-IoT devices in rural areas (see ***Figure 3***). The scene shows urban and suburban areas with good terrestrial coverage, with a rural region between them. The northern end of the urban area to the south is serviced by two terrestrial base stations, each with transmit powers of 40 dBm over a 20 MHz bandwidth. The suburban area to the north has one 40 dBm base station. For the rural area between, coverage is provided with a LEO satellite.

First, consider the coverage provided by the terrestrial base stations to NB-IoT devices located anywhere in the scene. To account for terrain masking, foliage shadowing and multipath effects for the signals traveling from the base stations to the NB-IoT devices, we employ a ray tracing model using Remcom's Wireless InSite® suite.[8] This model includes multipath propagation through the outdoor portion of the scene, including paths reflecting and diffracting from terrain and structures. This method incorporates full 3D multipath effects, including polarization and phase. In this scenario, the base stations are assumed to be vertically polarized, while the NB-IoT receivers are assumed to have linearly polarized 0 dBi antennas, with their polarization axes rotated 45 degrees

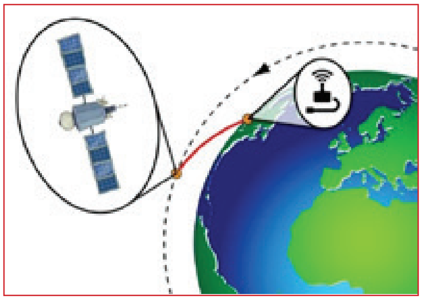

Fig. 1 A LEO satellite can communicate with IoT devices in rural or remote regions.

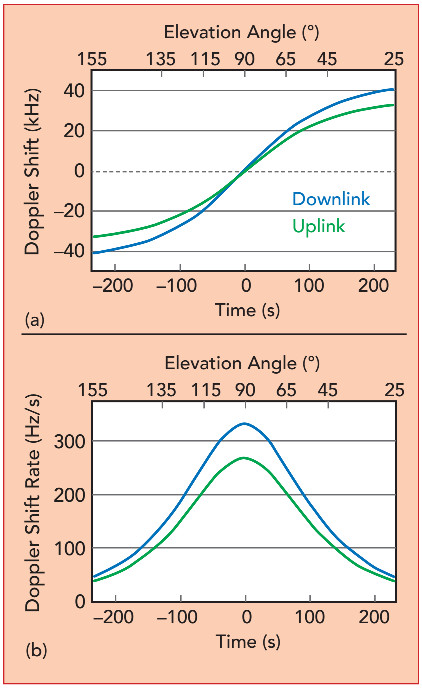

Fig. 2 Doppler shift (a) and Doppler drift rate (b) for a satellite in LEO orbit.

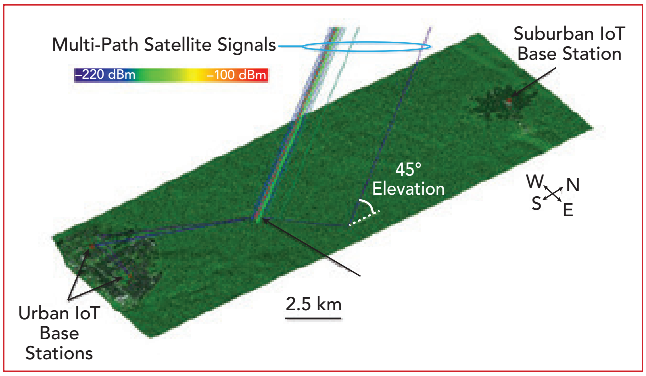

Fig. 3 **Urban-suburban-rural scenario used to model terrestrial and satellite coverage.**

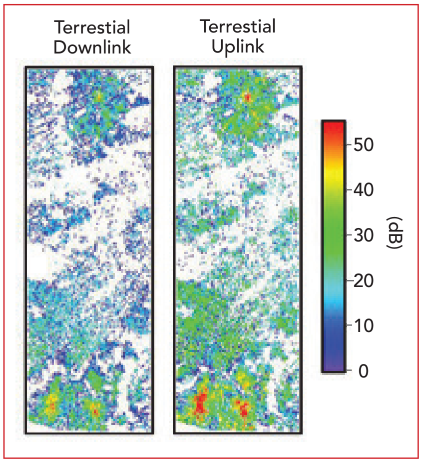

Fig. 4 **NB-IoT SNR for a terrestrial downlink and uplink.**

relative to horizontal. The NB-IoT receivers have a 9 dB noise figure and the ambient RF noise floor is assumed to be −167 dBm/Hz, which is consistent with measurements of 1.7 and 2.1 GHz RF noise in urban, suburban and rural environments.[9]

For NB-IoT receivers located anywhere in the scene, ***Figure 4*** shows the signal-to-noise ratio (SNR) for both the UL (1.7 GHz) and DL (2.1 GHz) signals with 180 kHz bandwidth. SNRs as high as 57 and 66 dB for DL and UL, respectively, are observed in the urban and suburban areas near the terrestrial base stations. For the rural area, however, the SNR often falls well below 0 dB (shown as transparent), due to terrain masking and foliage shadowing. Wireless InSite models attenuation from foliage by implementing the Weissberger model.[10]

The coverage in the rural area for the NB-IoT devices can be restored by a satellite overlay. The satellite signal is modeled within Wireless InSite and augmented with an in-house model by placing an isotropic transmitter within Wireless InSite at an apparent elevation angle and altitude determined from the calculations using the satellite-to-ground model described earlier. This accounts for the increased path loss due to refraction through the atmosphere.

To model DL coverage, the isotropic transmitter has an equivalent isotropically radiated power (EIRP) of 66 dBm less the power loss from atmospheric absorption, determined by the satellite-to-ground propagation model.[11] Atmospheric absorption within Wireless InSite is then disabled for the satellite links, as it is accounted for by this reduced EIRP. The 66 dBm EIRP assumes the satellite can provide a 36 dBm transmit power in a 180 kHz bandwidth and has an antenna gain of 30 dBi. The satellite antenna is assumed to be circularly polarized, which is typical for SATCOM in order to eliminate polarization rotation due to the Faraday effect. A 3 dB noise figure for the satellite antenna is assumed, as well as a noise temperature of 290 K for the UL,[12] resulting in noise power of −174 dBm/Hz. The DL retains the assumption of a 9 dB noise figure and a −167 dBm/Hz RF noise floor, appropriate for terrestrial communications at the frequency bands used in this scenario.

Figure 5 shows satellite DL and UL SNRs for the scene in Figure 3 at different elevation angles of the satellite above the horizon. SNRs less than 0 dB are transparent. The maximum SNR is achieved when the satellite is directly overhead (i.e., 90 degree elevation angle) because the propagation path loss and atmospheric absorption are minimized. At lower elevation angles, the SNR is compromised by shadowing from foliage and terrain. Despite these losses, an SNR above 0 dB can be maintained over most of the scene for elevation angles of 25 degrees or greater. Despite the lower transmit power of the NB-IoT devices (23 dBm is assumed for this analysis), the SNR for the UL is approximately 2 dB higher on average than for the DL, because the noise figure for the satellite receiver is 6 dB lower than for the low-cost NB-IoT devices. The ambient noise for the satellite is −174 dBm/Hz (approximately 7 dB lower than for the terrestrial systems) and the propagation path loss for the UL signal is reduced by 2 dB at a 90 degree elevation angle relative to the DL, due to the wavelength difference.

To quantitatively characterize the improved coverage obtained with the satellite overlay, ***Figure 6*** compares the cumulative distribution function (CDF) of SNR values for the terrestrial base station and the satellite at different elevation angles. To focus on the rural area, the CDF is computed for NB-IoT devices located in the central two-thirds of the scene shown in Figure 3. From the CDF for the terrestrial base

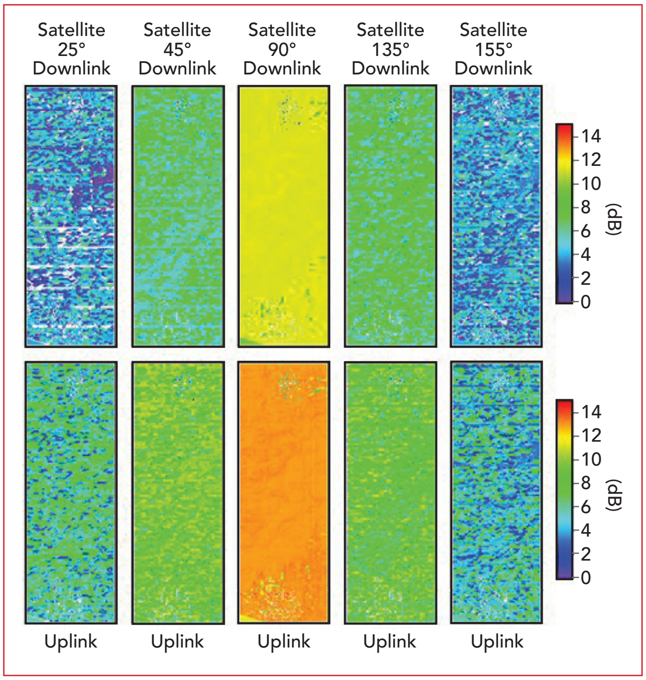

Fig. 5 **NB-IoT SNR for LEO satellite links vs. elevation angles.**

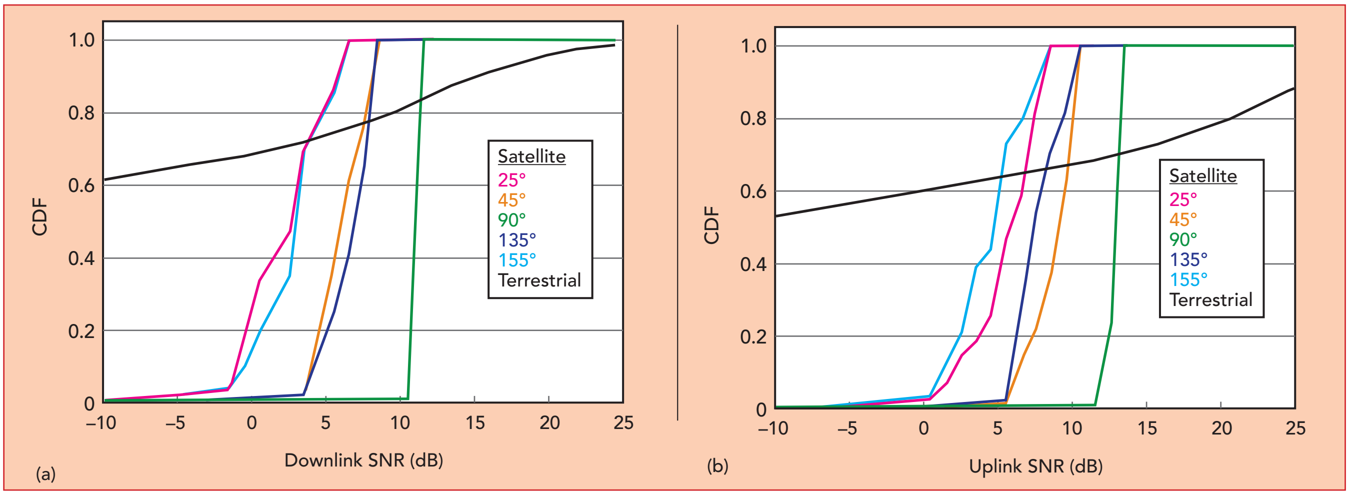

Fig. 6 **SNR CDF for the downlink (a) and uplink (b), comparing the terrestrial base stations with a LEO satellite at various elevation angles.**

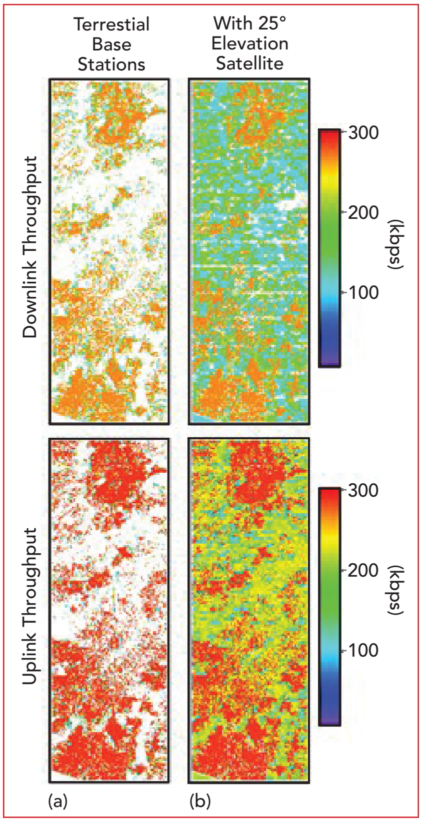

Fig. 7 **NB-IoT downlink and uplink throughput, comparing the terrestrial base stations (a) vs. satellite overlay (b), with the satellite at 25° elevation.**

stations, over 60 percent of the receiver/transmitter locations have SNRs less than 0 dB. In contrast, nearly 100 percent of the simulated device locations have SNRs greater than 0 dB for UL/DL satellite transmission at elevation angles as low as 25 degrees. When the satellite is overhead, most of the area achieves SNRs of 10 dB or better.

For a given SNR, modulation and coding scheme, the data throughput can be calculated. When using the full 180 kHz bandwidth, both the DL and UL in the NB-IoT standard use QPSK. ***Figure 7*** shows the throughput achieved by NB-IoT devices at different locations in the scene where the throughput estimate is based on the formula provided in 3GPP TS 38.306[13] and limited to the lower order QPSK modulations. Figure 7a shows the DL and UL throughput with just the terrestrial base stations; Figure 7b shows the throughput when the terrestrial base stations are supplemented by satellite coverage, where the satellite is assumed to be located at an elevation angle of 25 degrees. For the UL, the satellite overlay provides complete coverage across the scene, even for a satellite at 25 degrees. The coverage is nearly complete for the DL. As the satellite moves to higher elevations, the overall throughput continues to rise and attains a maximum throughout for the area when the satellite is overhead.

CONCLUSION

This case study demonstrates how satellite coverage can be modeled using predictive simulation. Such models can simulate the SATCOM channel, capturing important effects such as terrain masking, shadowing due to foliage and multipath fading, which are essential to a proper evaluation of the link budget. Further, ray tracing models can be used to identify cases where terrestrial coverage needs to be supplemented with a LEO satellite overlay to improve NB-IoT coverage in rural areas. These LEO satellites can provide coverage with relatively low latency, though this comes at the cost of complicating the communications channel, as large Doppler shifts must be compensated by the satellite and/or the UE.■

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