MORE THAN THE EYE CAN SEE

Coherence Time and Coherence Bandwidth of Troposcatter Links for Mobile Receivers

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Ergin Dinc and
Ozgur B. Akan

Troposcatter is a promising candidate for beyond-line-of-sight (b-LoS) links because it can provide near-instantaneous point-to-point communication at distances of up to 300 km with high reliability. However, troposcatter communication is an underdeveloped research area. In this article, we review the channel modeling techniques for troposcatter. Most importantly, we analyze the coherence time and coherence bandwidth of troposcatter links for mobile receivers for the first time in the literature. In addition, we review the diversity techniques for troposcatter channels by outlining open research problems and possible application areas.

Troposcatter Communication

Troposcatter is the scattering of signals due to tropospheric irregularities, and it can be used as a b-LoS communication medium at distances of up to 300 km. Although scattered power is directed in all directions, some of the troposcatter

Digital Object Identifier 10.1109/MVT.2015.2410786
Date of publication: 16 April 2015

1556-6072/15©2015IEEE

power can be received at the receiver by pointing the antennas to the horizon, as shown in Figure 1. The intersection region of the antenna beamwidths are called *troposcatter common volume*. Although around 2 GHz is well suited for troposcatter communications, modern troposcatter systems generally utilize the 4.4–5-GHz spectrum due to licensing problems [1].

Although troposcatter communication was a popular b-LoS communication technique, satellite communications (SATCOM) have dominated b-LoS communication applications because troposcatter communication requires large parabolic reflector antennas and high-power amplifiers due to high path losses. However, since satellite signals propagate over large areas, SATCOM links may have security problems, and communication links may be exposed to hostile jamming. In addition, SATCOM has high transmission delays of more than 500 ms. On the other hand, troposcatter links have delay spreads of only a few milliseconds [1]. Therefore, troposcatter channels are almost instantaneous. Since troposcatter communication systems utilize narrow-beam antennas, they provide a point-to-point communication link. Thus, they have a low detect/intercept probability compared with SATCOM. In addition, utilization of narrow-beam antennas significantly limits the Doppler spread that the channel experiences under mobility. Therefore, the troposcatter channel is expected to have a high coherence time, as discussed in the "Coherence Distance/Time and Coherence Bandwidth" section.

Troposcatter has become a promising candidate for b-LoS communications, especially after the development of advanced equipment. The state-of-the-art amplifiers can reach up to 2-kW transmit power, and modern troposcatter modems can operate at 22-Mb/s data rates [1], [2]. With technological advancements, troposcatter equipment is now small enough to be carried with military trucks. Thus, troposcatter may be utilized in mobile b-LoS applications as well. However, available studies consider only fixed troposcatter communication links. In addition, there are plenty of areas for improvement in troposcatter channel modeling because troposcatter is an underdeveloped research area. Therefore, we provide a detailed review of the troposcatter literature and point out open research issues and possible application areas.

The main contributions of this article are threefold. First, we provide an extensive review of troposcatter channel modeling. Second and most importantly, we utilize a ray-tracing channel modeling approach [3] to analyze the distance–frequency correlation function (DFCF) of the troposcatter links. The coherence time and coherence bandwidth of the channel are predicted to estimate the fading behavior of the channel under mobility for the first time in the literature. Third, we discuss the diversity techniques that can be employed in troposcatter links to eliminate the effects of short-term fading.

Channel Modeling Techniques

The geometry of troposcatter communications is quite different from conventional wireless communication systems, as shown in Figure 1. In addition, changes and fluctuations in atmospheric turbulence introduce variability in the scattered power according to environmental and atmospheric parameters such as wind, temperature, and climate. Therefore, we review channel modeling approaches for b-LoS troposcatter communications.

Statistical Methods

International Telecommunication Union—Radiocommunication Sector (ITU-R) P.617 [4] provides an estimation of the transmission losses (received power over transmit power) for troposcatter communications according to path geometry and climate. This method predicts annual and worst-month transmission losses for a defined nonexceeding percentage of the time. Since ITU-R's model is an empirical method, it provides reliable estimates for transmission losses. This model is most accurate for 5 GHz and below. Since the modern troposcatter applications mostly utilize 4.4–5-GHz bands to provide high bandwidths and data rates [1], [2], ITU-R P.617 is a promising method to estimate statistical troposcatter path loss values. Therefore, the ITU-R model is employed in several studies to analyze troposcatter channels. For example, Bastos and Wietgrefe [5] utilize a statistical method to estimate data rates that can be provided with troposcatter communications. In addition, the equations and parameters of the ITU-R P.617 model depend on the climate because atmospheric turbulence greatly changes with atmospheric conditions [4], as discussed in the "Atmospheric Effects" section.

We generate transmission loss results for 4.7-GHz carrier frequency with 10%, 50%, and 90% nonexceeding rates in Figure 2 using ITU-R P.617 for a maritime subtropical climate (climate 3 in [4]). Since troposcatter introduces high transmission losses, troposcatter systems utilize high-power amplifiers up to 2 kW [1]. Assume that the minimum received power for a high-data-rate troposcatter link is –90 dBm [2] and the transmit power is 60 dBm. In this case, the transmission loss threshold becomes 150 dB for the troposcatter link. As shown in Figure 2, the troposcatter link can provide a communication link at distances of up to

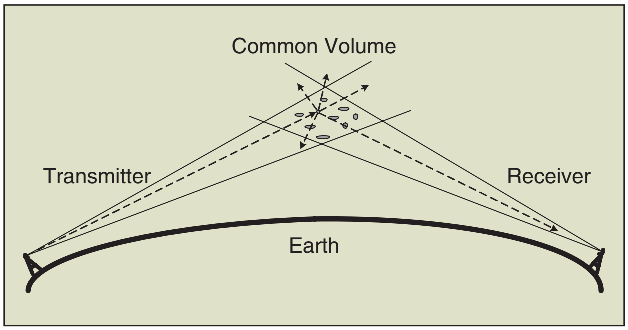

FIGURE 1 The b-LoS troposcatter communication paths.

350 km 90% of the time with these channel parameters. For lower ranges, the reliability of the troposcatter link further increases, and 250 km can provide a b-LoS link almost all the time, as suggested in [1].

Experimental Studies

There are several measurement campaigns for troposcatter communications [6]–[8]. These studies provide significant parameters for troposcatter links, such as path loss, fade duration, fading distribution, delay spread, and correlation results for different diversity techniques. In [7], the employment of space diversity in troposcatter channels is analyzed. In addition, the experimental results for path loss, fade duration, and fading distribution are provided. According to the experimental results, the power changes in the channel for small integration times show the Rayleigh distribution. Therefore, the b-LoS troposcatter channel can be modeled as a Rayleigh fading channel.

In [6], angle diversity for the troposcatter links is analyzed, and the correlation results for different beam separations are presented. The work in [8] includes the experimental correlation results for frequency diversity. Ndzi et al. [9] provide Doppler spread results for fixed troposcatter communication, and the maximum Doppler spread of the channel is reported as 15 Hz. Since this study considers fixed communication channels, the variations of the channel are caused by the atmospheric fluctuations. Therefore, the channel is slowly changing with the atmospheric variations by comparing megahertz- level bandwidths. Available experimental results can be utilized to verify the developed theoretical models.

Analytical Methods

There are also some analytical studies that model troposcatter channels. In [10], an analytical expression is provided for the power delay spectrum (PDS) of the channel. However, this method only depends on the scattering angle. Thus, this model cannot include the effects of atmospheric turbulence. Most importantly, in [11], we provide an analytical fading model for space, frequency, angle, and space-frequency diversity techniques, and their results are consistent with the experimental troposcatter studies [6]–[8]. Therefore, this fading model [11] can be utilized to predict the required spacings for these diversity techniques.

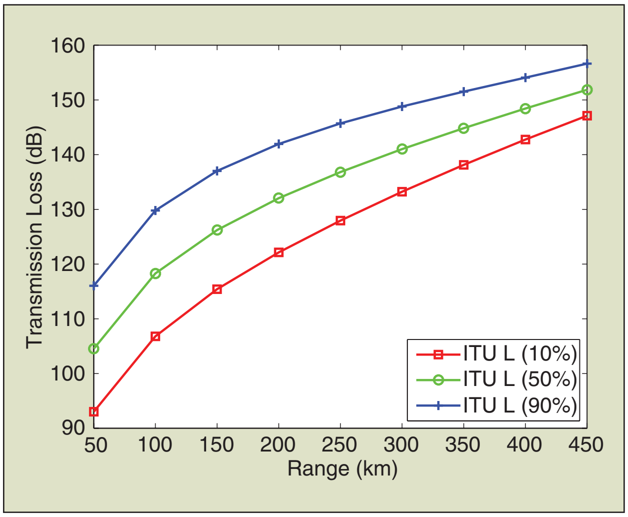

FIGURE 2 The path loss versus range for 4.7 GHz with the ITU-R model.

Ray-Tracing Methods

Ray-tracing methods are applied to many scattering channels, such as free-space optical links, and a recent study introduces a ray-tracing approach to model troposcatter channels [3]. In the ray-tracing troposcatter method, the power and delay of each ray is calculated using the developed differential scattering cross-sectional calculations. This way, the PDS of the channel is estimated using the path geometry and refractivity profile of the lower troposphere. Thus, ray powers are calculated with the bistatic radar equation [3]

$$P_r = \frac{P_t G_t G_r \sigma_V \lambda^2 \varrho}{(4\pi)^3 R_t^2 R_r^2}, \tag{1}$$

where P_t is the transmit power, $G_{t,r}$ are the transmitter and receiver antenna gains, ϱ is the polarization mismatch factor, σ_V is the differential scattering cross section, and $R_{t,r}$ is the distance between scattering point and transmitter/receiver.

In this method [3], atmospheric profiles are included with a scattering cross section that is developed using Rayleigh scattering approximation. To model atmospheric turbulence characteristics, the Kolmogorov spectrum technique is utilized, and the refractivity profile of the lower atmosphere is generated using the real-world measurements. However, we directly utilize ITU-R P.453 [12] to model the vertical refractivity. Using the approach in [3] and the generated refractivity profile [12], we present the PDS of the channel in Figure 3. As predicted, the shape of the PDS is close to the Rayleigh distribution shape. This is an expected result because b-LoS troposcatter links do not have a dominating LoS component. The resulting PDS can be used to predict important channel parameters, such as delay spread, coherence bandwidth, coherence distance, and the correlation between antennas for different diversity techniques. In this article, we utilize [3] to estimate the coherence time of the channel with mobility.

Atmospheric Effects

Troposcatter is strongly affected by climate because the scattering of signals at the lower troposphere significantly depends on atmospheric parameters. The statistical transmission-loss estimation method [4] provides the estimation of transmission losses for different climates. Figure 4 presents the transmission loss results at a 50% nonexceeding rate for different climates zones, and Table 1 lists the names of the climate zones. As shown, maritime-subtropical environments and sea environments have significantly fewer losses. The losses are significantly higher in desert and cold climates, thus troposcatter communication is less promising in these environments. The dependence on climate also can be seen in the ray-tracing methods via refractivity profiles that show significant dependence on climates [12].

In addition to climate, hydrometeors affect troposcatter links as well. For this reason, the effects of rain attenuation and rain scattering are analyzed in ITU-R P.452 [13]. However, [13] considers a single rain cell at the middle of the path with uniform rainfall distribution. Since b-LoS troposcatter links cover large areas, the link may be affected by multiple rain cells and real-world rain cells show nonuniform distributions. For this reason, rain attenuation in troposcatter links is an open research area as well. On the other hand, the effects of clouds and smaller hydrometeors can be ignored for the troposcatter links because modern troposcatter links utilize a 4.4–5-GHz frequency range that is too low to be affected by such small particles.

Available channel-modeling techniques provide important background for future troposcatter research. However, the statistical and analytical methods do not provide information about some important channel parameters, such as delay spread, coherence bandwidth, coherence time, and PDS of the channel. Since it is costly to perform experimental studies for each site, advanced theoretical troposcatter models are required to model troposcatter channels. Ray-tracing methods are promising because [3] they are able to estimate important channel parameters to characterize the troposcatter links: delay spread, coherence bandwidth, coherence time, PDS, and correlation between antennas. We also utilize the ray-tracing approach in [3] to analyze coherence time and coherence bandwidth to estimate fading behavior of the channel.

Coherence Distance/Time and Coherence Bandwidth

The state-of-the-art b-LoS applications may require mobile b-LoS links. However, available troposcatter studies only consider fixed troposcatter communications. The recent advancements in troposcatter equipment make possible transportable troposcatter equipment that can be mounted on vehicles. We believe that usage of narrow-beam antennas will limit the Doppler spread and troposcatter may be used in mobile b-LoS applications. For these reasons, we provide analysis for coherence distance/time to analyze mobility effects and coherence bandwidth to find the bandwidth levels in which the channel has flat fading.

We utilize the ray-tracing method presented in [3] to calculate the DFCF of troposcatter channel. In [3], we utilize real-world conditions to generate the refractivity profiles, but we directly utilize the refractivity model presented in ITU-R P.453 [12] for simplicity. In [3], a two-dimensional troposcatter channel is modeled. Therefore, we assume that movement will occur on the communication path, thus we slightly increase the range and calculate the correlation between PDSs to calculate the distance correlation. We calculate PDSs as described in the "Ray-Tracing Methods" section, and we correlate PDSs using MATLAB. For frequency correlation, we slightly increase the carrier frequency and

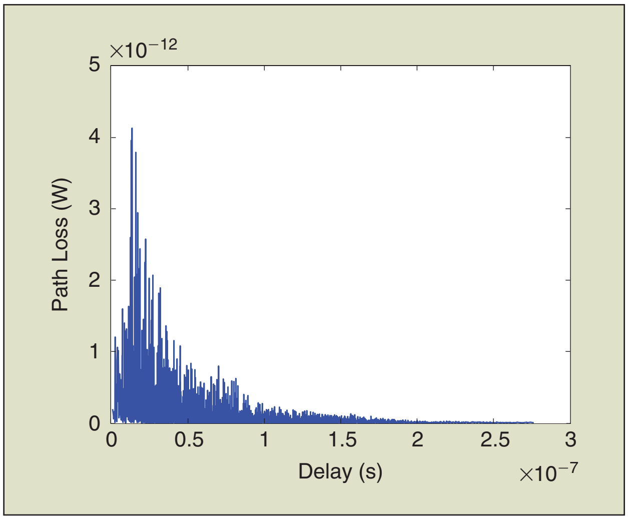

FIGURE 3 The PDS spectrum for a 150-km troposcatter link for 4.7 GHz.

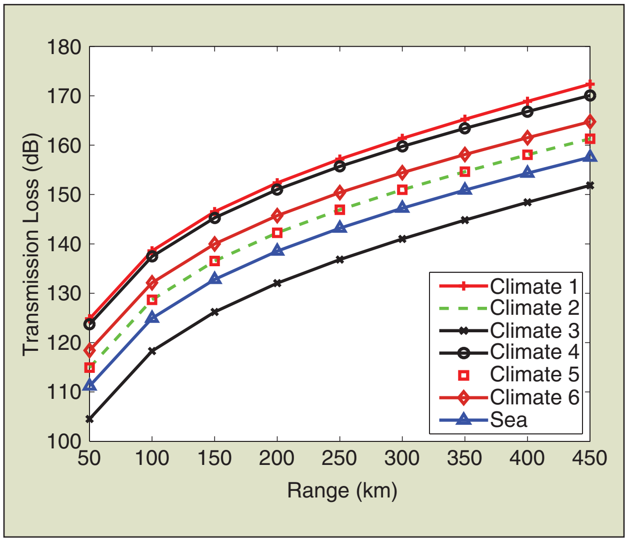

FIGURE 4 ITU-R P.617 transmission loss estimation results for 50% nonexceeding rates for different climate zones.

***TABLE 1** The ITU-R P.617 [4] climate zones.*

Number	Climate
1	Equatorial
2	Continental subtropical
3	Maritime subtropical
4	Desert
5	Continental temperate
6	Cold

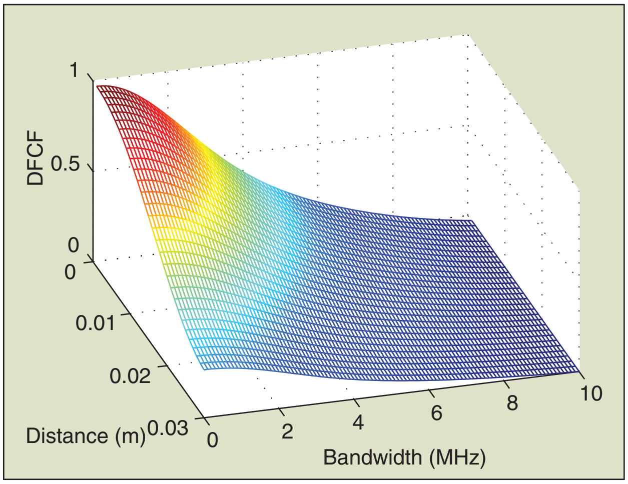

FIGURE 5 The DFCF of the troposcatter channel.

calculate the correlation between the resulting PDSs. Finally, we repeat these steps for both parameters to find the DFCF of the channel. The resulting DFCF of the troposcatter channel can be seen in Figure 5 for the parameters listed in Table 2. The channel becomes uncorrelated by almost half a wavelength separation, caused by the phase of the signals as modeled in [3].

Coherence Distance/Time

Fluctuations in troposcatter channels can be both caused by fluctuations of atmospheric turbulence or movement of receiver/transmitter. The Doppler spread of the fixed troposcatter links is measured in [9], and the Doppler spread for the channel is reported as 15 Hz at maximum. Thus, the main source of Doppler spread will be the speed of the vehicle for the troposcatter links because the Doppler spread will dominate the atmospheric changes due to mobility. For this reason, we assume steady atmospheric conditions in this article for simplicity.

Since troposcatter communications utilize very narrow beams (0.6°–1.5°) [1], [3], Doppler spread due to mobility is expected to be low because Doppler spread (D_s) is given as

$$D_s = \frac{\upsilon}{\lambda}\cos(\theta), \tag{2}$$

where υ is the speed of the vehicle, λ is the wavelength, and θ is the angle between the received ray and the horizon.

TABLE 2 ***The troposcatter communication parameters.***

Parameter	***Value***
Initial horizontal distance	150 km
Frequency	4.7 GHz
Antenna gains	41.5 dBi
Antenna beamwidths	1.5°
Antenna beam elevations	0.47°
Antenna diameters	3 m

In [3], beam elevation angles of 0.47° are utilized over sea conditions. For 1.5° beamwidth, θ will vary between 0.47° and 1.97° for the troposcatter link. Therefore, $\upsilon = 10$ m/s results in $\approx$ 157 Hz for this angle range by (2). As noticed in Figure 5, the coherence distance for the channel (D_c) can be determined as 0.03 m where the distance correlation function is low. The coherence time of the channel $(T_c = D_c/\upsilon)$ for $\upsilon = 10$ m/s becomes 3 ms. The relationship between coherence time and Doppler spread can be found as

$$T_c = \alpha\frac{1}{D_s}. \tag{3}$$

Using the ray-tracing simulations we calculate the coherence time as 3 ms and the Doppler spread of the channel is calculated as 157 Hz. Therefore, the resulting α becomes 0.47. The coherence time of the channel for different beamwidths and speeds can be directly calculated by (3) without any time-consuming ray-tracing simulations.

In this analysis, the coherence time of the channel is calculated as 3 ms, which is much lower compared to signal times at megahertz bandwidth levels. Therefore, the troposcatter channel will have slow fading at these mobility levels, and troposcatter communication can be performed under mobility conditions. However, received signal power will decrease as the range increases because the geometry of the channel will change with the increasing range. Therefore, the orientation of the antenna may be adaptively adjusted by adaptive antenna techniques. For these reasons, mobility in the troposcatter links is an important open research area.

Coherence Bandwidth

Figure 5 also presents the results for frequency correlation of troposcatter systems. The frequency diversity system becomes uncorrelated at 6 MHz bandwidth and above. The experimental results in [8] also suggest that the frequency correlation becomes low after a 6-MHz frequency separation. Therefore, our results are consistent with the experimental studies. The coherence bandwidth for 50% correlation can be used to estimate fading effect in the channel. If the bandwidth of the channel is greater than this value, the channel will experience frequency-selective fading. In Figure 5, 50% coherence bandwidth for steady link is around 2 MHz as in [11]. Therefore, the channel will experience flat fading for 2 MHz and lower bandwidths.

In addition, DFCF changes with both distance and frequency separation. Therefore, coherence time of the channel will decrease with increasing bandwidth. However, the signal time for 1–4-MHz bandwidths will be much lower compared with the coherence time of the channel, which is in the order of milliseconds, as calculated in the "Coherence Distance/Time" section.

Diversity Techniques

Troposcatter communication introduces high losses at b-LoS distances, as discussed in the "Channel Modeling Techniques" section, and fluctuating atmospheric turbulence results in short-term fading. The effects of fading become even worse with mobility. Therefore, employment of diversity techniques is required to alleviate the effects of short-term fading. To this end, we discuss possible diversity techniques that are suitable for troposcatter communications.

Space Diversity

In troposcatter systems, space diversity can be provided with either horizontally or vertically spaced antennas. Although vertical placement of large-parabolic reflector antennas (2.4–3-m diameter) does not seem practical, vertical placement of the antennas can provide four different troposcatter common volumes because the elevation angles of the vertically spaced antennas differ, as shown in Figure 6(a). For this reason, vertical space diversity may be preferable. Based on the available experimental studies [1], [7], and empirical recommendations by ITU-R [4], the required spacing for space diversity in the troposcatter should be 70–100λ for the antennas to have low correlation values. In addition, horizontal space diversity can be provided by horizontally spaced antennas. In [11], we provide an analytical model for horizontal space diversity. For uncorrelated antennas, horizontal space diversity requires 100λ or more spacing.

Angle Diversity

For angle diversity, same parabolic reflector antenna with two beams can be utilized and vertical or horizontal beam separations can be used. However, the amount of angle separation for horizontal-angle diversity is higher than the vertical case [1], [6]. Since troposcatter communication power is highly sensitive to the angle of antennas, the employment of vertical-angle diversity is more promising. In addition, vertical-angle diversity can generate four different troposcatter common volumes as shown in Figure 6(b). According to [6] and [11], vertical angle diversity provides uncorrelated antennas for 1–1.5 beamwidth beam separations. Since there will be a significant path difference between angle-diversity antennas, the upper beam will have significantly higher path loss values of up to 10 dB [6], [11]. Thus, gains of angle-diversity systems will be lower compared with space diversity, but the cost of the angle diversity is lower because it requires only one parabolic reflector compared with space diversity.

Frequency Diversity

In frequency diversity, signals are transmitted by different carrier frequencies that are adequately separated from each other. The required frequency separation is reported as 1% of carrier frequency in [1]. However, the experimental [8] and analytical [11] studies suggest that the troposcatter link with a 192-km range and 4.7-GHz carrier frequency becomes uncorrelated at 6-MHz frequency separation. Frequency diversity receivers can also be mounted on the same parabolic reflector, but utilization of the frequency spectrum increases with frequency diversity systems.

Polarization Diversity

Polarization diversity can be provided with dual-polarized antennas without the need for an additional parabolic reflector. Comtech [1] points out that vertical and horizontal polarizations have low correlation. Thus, polarization diversity is valid for troposcatter communications. Polarization diversity can be utilized with space or frequency diversity to provide quad diversity in troposcatter links; therefore, polarization diversity has high potential to improve the system performance.

Employment of diversity techniques in troposcatter links has high potential to increase system performance for possible high-data-rate employments. However, comparison and analysis of different diversity techniques is required. In particular, a combination of diversity techniques may be preferable in the troposcatter links, such as space frequency, space polarization, and frequency polarization. In addition, the performance of these diversity techniques under mobility may be investigated.

Application Areas

There is a significant demand for high-data-rate b-LoS communication links in both military and civilian applications [14]. Therefore, we investigate possible application areas of troposcatter b-LoS communications.

Military Applications

Military communication applications are sensitive to many parameters because network-centric operations require timely and accurate transmission of information

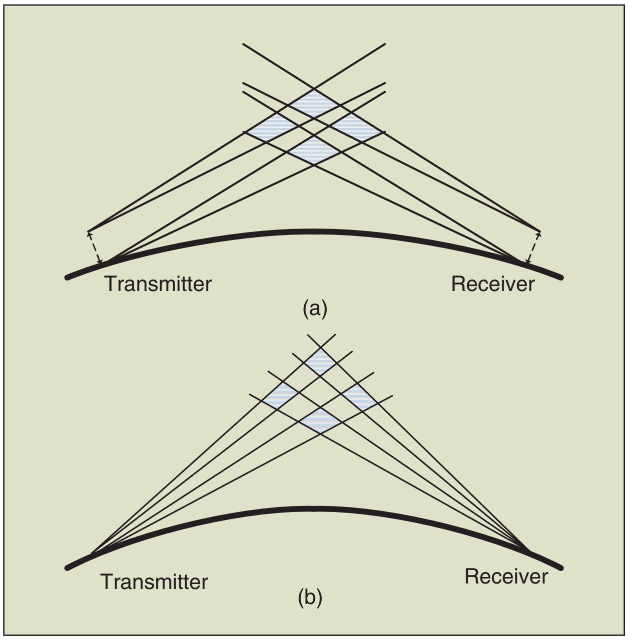

FIGURE 6 (a) Vertical space diversity and (b) angle diversity.

between units at all times with high reliability and security [14]. Therefore, military applications require low latency, high data rates, and high security. All of these concerns can be satisfied with troposcatter systems.

- *Latency:* Troposcatter communication provides near instantaneous point-to-point communication channels because the latency of the troposcatter channel is a few milliseconds [1].
- *High data rate:* Modern troposcatter systems are able to provide 22 Mb/s of data with high reliability [1].
- *Security:* Troposcatter systems utilize low-beam antennas. For this reason, the probability of detect/intercept is low for troposcatter links.

For these reasons, troposcatter is a promising candidate for modern military applications where high-data-rate point-to-point communication is required.

Civilian Applications

Civilian applications also require high-data-rate b-LoS links. The most important candidate is offshore gas and petroleum production platforms [15]. These platforms are generally located in open seas where LoS microwave communication is not possible. Offshore platforms generally utilize underwater fiber cables or SATCOM to communicate with land stations. However, underwater fiber cables are too expensive even though they provide the highest communication quality. High-capacity SATCOM has a much higher operational cost compared with underwater fiber and troposcatter [15]. In civilian applications, the cost of the system becomes an important constraint. Even if the initial cost for the troposcatter systems is higher than SATCOM, troposcatter becomes cost effective in the long run compared with SATCOM at high data rates, as described in [15]. Therefore, b-LoS troposcatter communication can be utilized for high-data-rate civilian applications.

Conclusions

In this article, we review the channel modeling techniques and possible diversity techniques that are suitable for troposcatter communications. In addition, we present simulation results for DFCF of the channel to estimate coherence time and coherence bandwidth of the troposcatter channel with mobility. According to our analysis, the coherence time of the troposcatter channel is in the order of milliseconds. Therefore, mobility in troposcatter communications is promising, and it is a significant open research area. Furthermore, we discuss the possible application areas for b-LoS troposcatter communications.

Author Information

Ergin Dinc (edinc@ku.edu.tr) received his B.Sc. degree in electrical and electronics engineering from Bogazici University, Istanbul, Turkey, in 2012. He is currently a research assistant at Next-Generation and Wireless Communications Laboratory and is pursuing his Ph.D. degree at the Electrical and Electronics Engineering Department, Koc University, Istanbul, Turkey. His current research interests include communication theory, beyond-line-of-sight communications with troposcatter, and atmospheric ducts. He is a Student Member of the IEEE.

Ozgur B. Akan (akan@ku.edu.tr) received his Ph.D. degree in electrical and computer engineering from the Broadband and Wireless Networking Laboratory, School of Electrical and Computer Engineering, Georgia Institute of Technology in 2004. He is currently a full professor with the Department of Electrical and Electronics Engineering, Koc University, and the director of the Next-Generation and Wireless Communications Laboratory. His current research interests are in wireless communications, nanoscale and molecular communications, and information theory. He is an associate editor of *IEEE Transactions on Communications, IEEE Transactions on Vehicular Technology, International Journal of Communication Systems* (Wiley), *Nano Communication Networks Journal* (Elsevier), and *European Transactions on Technology*. He is a Senior Member of the IEEE.

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