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# Performance Evaluation of High-Frequency Mobile Satellite Communications

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**ABSTRACT** Communication satellites have a much longer propagation delay than terrestrial communication networks such as cellular or WiFi. In addition, as the carrier frequency moves up, mobile satellite communications show worse performances than the conventional fixed satellite communications. The mobile satellite service (MSS) has not been actively pursued with long latency at high-frequency bands for future applications. In this paper, the adverse impact of long propagation delay in the conventional satellite system is investigated with various user mobility and Doppler-shifted carrier frequency. The satellite network is modeled as a basic delayed feedback channel system and the communication performance is analyzed under delayed channel state information (CSI) for assessing the system feasibility in mobile conditions. The results of performance analysis are provided at high-frequency bands with high-speed user movement, specifically on the outage probability and the channel capacity exploiting three types of channel models: conventional land mobile satellite (LMS) channel models of E. Lutz and C. Loo, and Nakagami fading model. In the circumstance with various user speeds, system performances are evaluated with different propagation delays in the LMS channel models and for line-of-sight (LOS) components in the Nakagami fading. In addition, the conventional models are compared depending on different altitudes for geostationary orbit (GEO), medium earth orbit (MEO), and low earth orbit (LEO) satellites, as well as high-altitude platforms (HAP).

**INDEX TERMS** Mobile satellite communications, delayed channel state information (CSI), land mobile satellite (LMS) channel model, outage probability, channel capacity.

## I. INTRODUCTION

Satellites can provide global coverage and persistent communication services during emergencies when ground infrastructure systems have been damaged [1]–[3]. Satellite communication systems are one-way or two-way radio frequency (RF) transmission systems based on local oscillators in launched satellites, which operate in a wide bandwidth range of the 1–30 GHz band. These systems are essentially different from terrestrial systems in terms of the resources used, cost, transmission technologies, and in how they are deployed and operated. The satellite network consists of the space, ground and control segments, specifically satellites, ground gateways and network management stations, respectively. In general, satellite systems can be classified according to the altitude at which they are deployed and the types of services they provide. With respect to altitudes, the systems are categorized into three classes: low earth orbit (LEO; 200–2000 km), medium earth orbit (MEO; 2000–20000 km) and geostationary orbit (GEO; 36000 km). Depending on the service type, they can be broadly divided into those providing fixed satellite services (FSS), broadcast satellite services (BSS) and mobile satellite services (MSS).

The main target applications have shifted from TV broadcasting and telephony trunking to data packet transmissions for Internet services. Recent developments in relation to 4G/5G technology have brought attention on constructing satellite-terrestrial heterogeneous networks. Traditional satellite networks determine user scheduling and data forwarding issues at ground hub stations, and satellites have served as bent-pipe relays based on decisions made on the ground, mostly due to the high cost of carrying heavy computing components into space. It is expected that the on-board processing (OBP) scheme will become feasible for use in the

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sky due to the rapid growth of application-specific integrated circuit (ASIC) or powerful central processing unit (CPU) technologies.

If communication networking is facilitated in the on-board payload, the total end-to-end latency of satellite systems can be reduced due to the elimination of the unnecessary round-trip delay to receive the control signal and can conserve the invaluable RF spectrum by reducing the need for feeder links from/to the gateways [4]. Moreover, with the OBP scheme, satellite networks can support higher throughput in multiple beams, and up/down links and potentially inter-satellite links (ISL) can efficiently exploit routing and scheduling designs. This can lead to the creation of a high-throughput satellite (HTS) which can offer services with 100 Gbps and facilitate a high volume of onboard computation with novel state-of-the-art technologies [5]–[7].

Thus far, conventional satellite communication systems have primarily utilized frequency bands of 1 to 4 GHz, which are L or S band. Due to saturation at the low frequency bands, however, high frequency bands above 20 GHz, such as Ka band (27–40 GHz), have been increasingly explored for their ability to provide stable broadband services. In addition, satellite networks should provide services in mobile environments [8], known as the MSS, to keep up with terrestrial mobile networks, including 5G technology, which has achieved rapid advancements in recent years [9]–[11]. The MSS system when operated at the super high frequency (SHF) has several weaknesses: First, satellite signals are very sensitive to moisture absorption and weather impairments, such as rain attenuation. Second, long latency, a main characteristic of GEO satellite systems, can become a factor critically affecting mobile service performance capabilities with fast time-varying channels, as it is very difficult to reflect the fast time-varying channel characteristics in long-latency satellite environments. Performance degradation caused by user movements is unavoidable because the channel variation from multipath and mobile environments is usually much faster than the round-trip delay (RTT: 250 ms) of the GEO satellite link. It is necessary to study the impact of both SHF and high speed environments in order to provide stable performance in the future MSS systems.

Many previous studies have analyzed various satellite systems and attempted to improve the system performances. Recent studies have emphasized the necessity of providing the stable communications over extremely high frequency bands (30–300 GHz) [12]. The importance of mobile services in satellite communication systems has also been investigated [13]. Studies of high frequency bands have focused on the aspects of performance analysis and enhancements from two perspectives: applications of principles in general satellite systems to high frequency band systems and analyses of land mobile satellite (LMS) channels at high frequency bands. For existing systems at high frequency bands, new adaptive coding and modulation (ACM) schemes and a two-state satellite channel model have been proposed [14]. Throughput with a link adaptation technique has been analyzed at Ka band [15]. A feeder link switch to high frequency band has been proposed [16]. The performance improvements achieved by multiuser detection and pre-coding have been investigated considering the self-interference generated from the multibeam satellite [17]. In addition, for high-throughput satellites, a dynamic scheduling method which uses a priority code scheme to support a large number of users has been proposed [18]. A novel antenna array for high data rates for mobile satellite television broadcasting at Ku (12–18 GHz) band was designed [19], and channel filters for shadowing detection under land mobile channel conditions at Ka band according to the attenuation factor and terminal status have been analyzed [20].

Other studies of LMS channels have involved communication performance analyses by traditional models such as Lutz's and Loo's LMS channel model [21], [22]. System performance capabilities at Ku and Ka bands have been analyzed and evaluated in terms of the probability distribution function (PDF) [23] or the cumulative distribution function (CDF) [24] of the received signal, as well as the bit error rate (BER) [25]. Suitability and usefulness issues were investigated in both Lutz's and Loo's channel models in high frequency band satellite communication systems, with rain attenuation in consideration of the channel states, where user movements are also considered to take into account the MSS environment [26].

In terrestrial communications, Rayleigh fading with the Doppler effect in the general multipath scenario is proposed for new sum-of-sinusoids statistical simulation models to analyze the statistical properties [27]. Peer-to-peer wireless circumstances are analyzed with mobile stations [28]. Some studies for application of the underwater analysis [29] and the security problem [30] with the Doppler effect have been evaluated. Services for global navigation satellite systems (GNSS) of mobile nodes are investigated to seek for performance improvement by mitigating the impact of the Doppler effect [31].

The influence of the Doppler effect on satellite communication was primarily considered for fast movements of LEO satellites in previous studies [32]–[35]. The Doppler effect in GEO satellites with mobile stations at low frequency bands, such as [36], was rarely analyzed. Though the Doppler effect had to be investigated due to the requirement of high frequency bands, most researches focus on the weather effect at high frequencies without detail of Doppler parameter design. The system analysis and evaluation that only utilize the conventional LMS channel as a stochastic model was conducted in [15], [19], [20], [23]–[26] as previously mentioned in related work.

There are a few studies [37],[38] that have addressed the impact of the user mobility. However, they were mainly focused on the Doppler spread and antenna pointing loss rather than the feedback channel state information (CSI) and the frequency shift by the Doppler effect. They proposed novel models by taking into account the Doppler spread due to user mobility in the LMS channel with diverse atmospheric impairments through a channel estimation method. In addition, the antenna pointing loss was investigated in terms of the tracking error of the directional antenna for influence of continuous movements. As ground users move at high speeds, it becomes extremely difficult to feedback CSI on time over long-latency high frequency satellite links, which results in delayed feedback environments. One solution is to deploy OBP satellites, which facilitate data processing in space segments and forward to other satellites or re-transmit to earth stations. This has the advantage of reducing the end-to-end latency by eliminating the need for unnecessary round-trip delays.

In addition, some papers have presented performance improvement by CSI. The terrestrial communication network can achieve enhanced performance with feedback CSI in general [39]. In the multipath propagation condition, the multiple antenna system can achieve low error rates and high spectral efficiency [40]. With a partial CSI transmitter and a full CSI receiver, achievable transmission rates and optimal coding schemes have been investigated by means of information theoretical analysis [41]. The relationships between pure information and CSI transmission have been investigated and an attainable trade-off region between pure information rates and state estimation errors has been presented [42]. Furthermore, the CSI can be exploited not only for communications but also for another application field pertaining to the identification of patterns by dementia patients [43],[44]. Although the imperfect CSI was considered in other studies, there are few discussions that consider both high-speed and high-frequency band conditions with imperfect CSI in the satellite communications.

In this paper, we investigate the potential improvement and limitation of the system performance by means of OBP considering both high-speed and high-frequency bands under the conditions of long latency and rapid channel variation by fast movement. The delayed feedback CSI is analyzed in mobile satellite and wireless communication systems and the system performance is assessed in terms of the outage probability and channel capacity. For this, a performance analysis is conducted to the satellite system using stochastic channel models and a simple channel compensation method is evaluated for certifying the feasibility of providing reliable mobile communication services in the space system. Subsequently, power consumption performance is investigated along with channel capacity increments by compensating for channel attenuation with delayed feedback CSI depending on the system altitude and user speed.

The structure of the paper is organized as follow: Section II introduces the conventional channel models for satellite communications and incorporates the Doppler effect. Section III shows the system performance improvement with delayed feedback CSI in high velocity environments. A simple power control scheme is illustrated based on the delayed feedback CSI under the minimum and maximum power constraints. In section IV, the simulation results on the effect of the delayed feedback CSI are provided in terms of the channel capacity and average power consumption. The conclusion is given in section V.

## II. ANALYSIS OF CONVENTIONAL CHANNEL MODELS

In this section, the conventional Lutz's and Loo's LMS channel models are analyzed considering the Doppler effect due to user movements and the use of the high frequency band. The system performance is evaluated with mobile satellite channel models according to the difference in the movement speed and LOS (line-of-sight)/NLOS (non-LOS) depending on the road environment.

We consider the channel capacity $C$:

$$C = BW \cdot \log_2 \left(1 + \frac{h^2 \cdot P}{\rho \cdot BW \cdot N_0}\right), \tag{1}$$

where $BW$ is the channel bandwidth, $N_0$ is the noise power, $h^2$ $(\leq 1)$ is the power attenuation due to channel fading, and $P$ is the transmitted signal power. $\rho = (4\pi d/\lambda)^2$ denotes the path-loss attenuation with the distance between transmitter and receiver $d$ and the wavelength $\lambda$. The channel capacity should be averaged over the random variable $h^2$, which is computationally complicated. Instead, the approximate Gaussian channel capacity is upper-bounded by Jensen's inequality [45], as follows:

$$\mathbf{E}\left[BW \cdot \log_2 \left(1 + \frac{h^2 \cdot P}{\rho \cdot BW \cdot N_0}\right)\right] \leq BW \cdot \log_2 \left(1 + \frac{\mathbf{E}\left[h^2\right] \cdot P}{\rho \cdot BW \cdot N_0}\right). \tag{2}$$

The upper bound of Jensen's inequality exploits the expected value of the channel gain, which results in the approximate form of the Gaussian channel capacity. We investigate this upper bound of the channel capacity for maximum system performance.

### A. LUTZ'S LMS CHANNEL MODEL

In the Lutz's LMS channel model, the fading process is modeled by the two-state Markov chain [45]–[48] to represent good and bad channel states, and the transition probability with feedback delay and the channel memory component can be obtained by [39, Appendix B]. The Rician distribution is used for good states when multipath fading has a dominant direct signal component. The corresponding probability density function (PDF) $p_{Rician,Lutz}(S)$ is expressed as

$$p_{Rician,Lutz}(S) = k \cdot \exp\left[-k(S+1)\right] \cdot I_0\left(2k\sqrt{S}\right), \tag{3}$$

where $S$ is the signal power, $k$ is the K-factor of the Rician distribution, denoting the power ratio between the dominant component (LOS) and the other signal components, and $I_0(\cdot)$ is the modified Bessel function of the zeroth order. On the other hand, in the bad channel state, the multipath signal has no dominant component under severe shadowing (NLOS). Channel fading follows the Rayleigh/lognormal distribution in what is known as the Suzuki channel model. The PDF

$p_{Suzuki,S}(S)$ is determined by

$$p_{Suzuki,Lutz}(S) = \int_0^\infty p_{Ray,Lutz}(S \mid S_0) \cdot p_{LN,Lutz}(S_0)\, dS_0, \quad (4)$$

where $p_{Ray,Lutz}(S \mid S_0)$ and $p_{LN,Lutz}(S_0)$ represent the PDFs of Rayleigh and lognormal fading, respectively, and $S_0$ is the short-term mean of the received signal power. The Doppler effect is taken into account to reflect user movements and speeds by grafting the Doppler frequency into the fading channel. The detailed channel model change that reflects the Doppler effect due to user mobility is explained in [26].

In [26], the Doppler effect is reflected to fading channels in the Rician and Rayleigh models. The shifted frequency $f_d$ [49], [50], by the Doppler effect due to user movement can be defined as

$$f_d = f_0 \frac{v}{c} \cos\theta, \quad (5)$$

where $f_0$ is the carrier frequency, $v$ and $c$ denote the speed of user and light, respectively, and $\theta$ is the angle of incidence of multipath signals. The fading $e(t)$, which is affected by the Doppler effect, can be defined as

$$e(t) = (X + a_0)\cos(2\pi f_0 t) - Y \sin(2\pi f_0 t), \quad (6)$$

where $a_0$ is the signal strength of the dominant path and $X$ and $Y$ denote the channel scattering due to fading, presented by $X = \sqrt{1/M} \sum_{i=1}^{M} \cos(2\pi f_d t \cdot \cos\alpha_i + \phi_i)$ and $Y = \sqrt{1/M} \sum_{i=1}^{M} \sin(2\pi f_d t \cdot \cos\alpha_i + \phi_i)$. $M$ is the number of multipath, $\alpha_i$ is the angle of the incoming wave on the $i^{th}$ path, and $\phi_i$ is the relative component phase on the $i^{th}$ path. Then, the received signal $r(t)$ reflects the channel variation due to user mobility and channel fading, as follows:

$$r(t) = \sqrt{\frac{1}{M}} \sum_{i=1}^{M} \exp\left[j\left(2\pi\left(f_0 + f_d\right) t \cdot \cos\theta_i + \phi_i\right)\right]. \quad (7)$$

Lutz's LMS channel model is evaluated in terms of the approximate Gaussian channel capacity based on the GEO satellite communication system according to different roads in urban (with the user speed of 40 km/h) and highway (120 km/h) environments. Each road environment differs in terms of the amount of the dominant signal component due to the surrounding buildings or structures.

Using the parameter values in [51], the K-factor are assumed to be $k = 10$ on highways and $k = 2$ in urban areas in our simulations, as expressed in (3). In addition, the ratios between the mean durations of good and bad states [21] are calculated for the transition probabilities of the two-state Markov chain model to represent user movement. Moreover, the frequency bands of 2 and 20 GHz are compared to investigate whether the traditional stochastic channel model is applicable at high frequency bands and to analyze the influence of the Doppler shift in mobile communication environments. The system performance of Lutz's model is shown in Fig. 1 for the highway and urban conditions depending on the different frequency bands and the Doppler effects. The available maximum transmission power in GEO satellite is assumed to be 1 kW and the system throughput is analyzed over the entire available transmit power range.

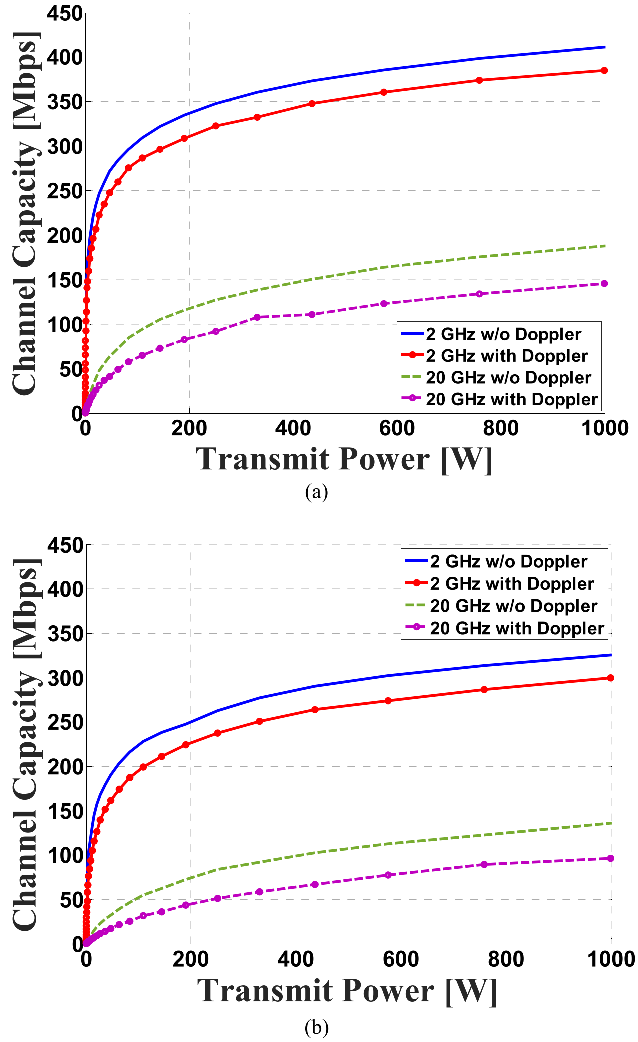


**FIGURE 1.** The channel capacities (a) in the highway environment and (b) in the urban environment, according to the different frequency bands and the Doppler effects for Lutz's LMS channel model.

It is found that the impact of frequency band migration from 2 to 20 GHz is highly significant on the system performance, as indicated between the full and dotted lines in Fig. 1. The capacity at 20 GHz is reduced to less than half of that at 2 GHz. The system throughput is degraded further by the Doppler effect due to user mobility, and the degradation is worse at 20 GHz than at 2 GHz. The maximum amounts of performance degradation at each frequency band due to the Doppler shift are as follows: 1) in the highway environment, up to 6.35 % at 2 GHz and 22.6 % at 20 GHz, respectively, as shown in Fig. 1(a). 2) In the urban environment, up to 8.43%

at 2 GHz and 27.35 % at 20 GHz, respectively, as shown in Fig. 1(b).

### B. LOO'S LMS CHANNEL MODEL

In Loo's model, the signal is modeled using the sum of the lognormal and Rayleigh random variables with independent phases:

$$r \cdot \exp(j\theta) = z \cdot \exp(j\psi_0) + w \cdot \exp(j\psi), \tag{8}$$

where $r$ is the signal amplitude, $\psi_0$ and $\psi$ correspondingly denote uniformly distributed phases between 0 and $2\pi$, $z$ and $w$ likewise represent the lognormal and Rayleigh distribution. The good channel state follows Rician/lognormal distribution $p_{Good,Loo}(r)$ which is given as follows:

$$p_{Good,Loo}(r) = \frac{r}{\left(b_0\sqrt{2\pi d_0}\right)} \cdot \int_0^\infty \frac{1}{z} \cdot \exp\left[-\frac{(\ln z-\mu)^2}{2d_0} - \frac{r^2+z^2}{2b_0}\right] I_0\left(\frac{rz}{b_0}\right) dz, \tag{9}$$

where $b_0$ denotes the average scattered power of multipath signals, and $d_0$ and $\mu$ represent the variation and mean of shadowing components, respectively. The Rayleigh PDF function $p_{Ray.,Loo}(r)$, which represents the bad channel state, is given by

$$p_{Ray.,Loo}(r) = \frac{r}{b_0}\exp\left[-\frac{r^2}{2b_0}\right]. \tag{10}$$

In Loo's LMS channel model, the chief difference from the Lutz's is that the shadowing effect by the lognormal component is applied in the good channel state, whereas Loo's model is a single-state channel model. However, a two-state Markov chain model is also utilized to distinguish simply between the good and bad channel states. Then, the system performance is analyzed for the same road environments, frequency bands and parameters assumed in the simulation of Lutz's model.

Fig. 2 shows the channel capacity curves for the Loo's channel model using the Gaussian approximation for highway and urban environments. The simulation results are very similar to those from Lutz's model. As the road environment changes from highway to the urban condition, it can be observed that the system throughput is reduced due to shadowing by the surrounding buildings or structures. Specifically, as in Lutz's channel model, when the carrier frequency band moves to the high frequency band (20 GHz), we confirm that the system throughput is degraded more seriously at less than half of 2 GHz and that the performance degradation is more severe due to the Doppler effect that arises when there is user mobility. The comparison of two channel models and the corresponding results are summarized in Table I.

## III. SYSTEM MODEL FOR EVALUATION

GEO satellites have long propagation delays of almost 250 ms for a round trip, which is much longer than the channel coherence time in the mobile communication system.

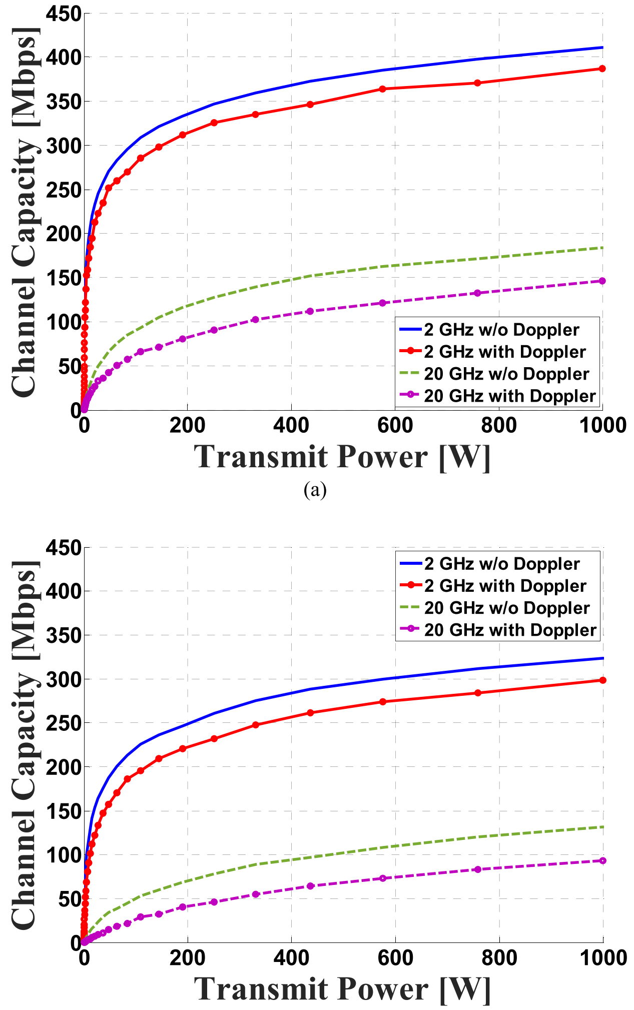


**FIGURE 2.** The channel capacities (a) in the highway environment and (b) in the urban environment, according to the different frequency bands and the Doppler effects for Loo's LMS channel model.

**TABLE 1.** Comparison of Lutz and Loo channel models.

| | Condition | | Lutz's Model | Loo's Model |
|---|---|---|---|---|
| Channel Model | State | Good | Rician | Rician /lognormal |
| | | Bad | Rayleigh /lognormal | Rayleigh |
| Performance Loss | Highway | 2 GHz | 6.35 % | 5.72 % |
| | | 20 GHz | 20.32 % | 22.60 % |
| | Urban | 2 GHz | 8.43 % | 7.82 % |
| | | 20 GHz | 27.35 % | 28.72 % |

Fast time-varying channels due to the movement of mobile users or terminals can make channel estimation extremely difficult, incurring both estimation errors and system performance degradation. As a countermeasure, the system may exploit sufficient power margins (i.e., over-budget power) for bad channel conditions or other resource allocation algorithms. Here, we analyze the system performance and evaluate the effects of a simple power control method in terms of the outage probability for different altitudes and mobile user speeds when the system with OBP architecture utilizes the delayed feedback system. Eventually, the effectiveness is investigated for the OBP satellite system at the high frequency band in the high speed environment, which has been a bottleneck for advancing satellite communications.

In the previous section for analysis of channel capacity both Lutz's and Loo's models show very similar results. Two system models are addressed: Lutz's LMS channel model and Nakagami fading. The Lutz's LMS channel is set to a fixed LOS condition in highway environment with clear roads for an evaluation of the proposed channel compensation scheme in accordance with the conditions defined in Section II. On the other hand, the Nakagami model can control the channel condition for the LOS component with a shape parameter, unlike Lutz's channel model. The PDF [52] of the Nakagami fading channel, $p_{Nakagami}(r)$, can be expressed as

$$p_{Nakagami}(r) = \frac{2m^m}{\Gamma(m)\,\Omega^m} r^{2m-1} \exp\left(\frac{-mr^2}{\Omega}\right), \quad (11)$$

where $m$ is a shape parameter, $\Omega$ is a controlling spread, and $\Gamma(\cdot)$ is the gamma function. It is typically a single-state model and not classified for channel states of good or bad, unlike the two-state Markov model by Lutz. The channel variation is presented by the level crossing rate (LCR) [Hz] [50], which measures the rapidity of the fading or the frequency of the envelope change. It can be given by

$$N_{Nakagami}(\rho) = \sqrt{2\pi} f_d \frac{m^{m-(1/2)}}{\Gamma(m)} \rho^{2m-1} \exp\left(-m\rho^2\right), \quad (12)$$

where $\rho$ is a normalized threshold. The channel has different envelope changing rates according to the Doppler frequency, $f_d$ in (12). For a positive value of the LCR, the normalized envelope threshold is defined as $\rho = 1$. The channel envelopes following the Nakagami distribution are generated at every level crossing cycle according to shape parameter $m$. The channel generation algorithm through the LCR value was already devised and exploited in [19].

It is assumed that the signal is transmitted every 1 ms for both channel models and the OBP satellite receives and processes the feedback CSI from the ground stations or users. With the current channel state $h(t)$ at time $t$, the delayed feedback CSI is given by $h(t-d)$ with delay $d$ from the ground feedback, by which the delay time is determined by the altitude of the satellites or aerial platforms. Transmit power control is conducted for channel compensation based on delayed feedback CSI, and the system performance is investigated in terms of the average transmission power consumption and changes in the channel capacity. Systems at different altitudes, such as GEO, MEO, LEO, or high-altitude platform (HAP) are compared to assess the impact of different feedback delays on the support of stable system performance in Lutz's channel. In the scenario with the Nakagami model, the propagation delay is set to that of the GEO satellite to investigate the influence of the channel states according to the LOS components and user movements.

A ratio of $h_{comp}(t)$ is introduced between the current (and actual) CSI $h(t)$ and the delayed feedback CSI $h(t-d)$,

$$h_{comp}(t) = \frac{h(t)}{h(t-d)}, \quad (13)$$

which represents the accuracy of the delayed feedback CSI and is utilized as an index to evaluate the impact on the transmit power control process. The ratio is classified in three cases: $h_{comp}(t) < \alpha, \alpha \le h_{comp}(t) < \beta$ and $h_{comp}(t) \le \beta$, with the parameters of $\alpha$ and $\beta$ for the boundaries. Each case is explained in detail below:

1) If $h_{comp}(t) < \alpha$, the feedback channel information reports a much better channel condition than the current CSI.

2) If $\alpha \le h_{comp}(t) < \beta$, the feedback CSI is in the similar range of the current CSI.

3) If $h_{comp}(t) \ge \beta$, the feedback CSI is much worse than the current CSI.

The first case corresponds to a service outage due to the current bad channel condition, whereas the third case incurs the risk of using excessive power during the power control process because the feedback channel indicates a worse condition than the current CSI.

The parameters of $\alpha$ and $\beta$ can be presented by

$$\alpha = 1 - \frac{3\sigma}{\mathbf{E}[h(t-d)]}$$
$$\beta = 1 + \frac{3\sigma}{\mathbf{E}[h(t-d)]} \quad (14)$$

where $\sigma$ denotes the standard deviation of the channel gains as defined in Lutz's LMS channel model in Section II, and $\mathbf{E}[h(t-d)]$ is the expectation of the delayed feedback CSI. In the Nakagami model, the values of the standard deviation and the expectation are calculated using the observed channel envelope data. Here, $3\sigma$ is adopted from the three-sigma rule [53], which statistically represents the 99.7 % range of the random variable in terms of the mean and the standard deviation. Note the normalization by the expectation value of the channel gain for the unitless ratio of $h_{comp}(t)$.

In contrast, as the default system transmitting signals with fixed transmit power $P_{def}$ is unlikely to support user requirements for service rates, a simple transmit power control scheme can be adopted for stable communication services based on the delayed feedback CSI. The controlled transmission power $P_{ctrl}$ can be obtained as follows:

$$P_{ctrl} = \begin{cases} P_{max} & \text{if } h(t-d) < a \\ \frac{P_{def}}{h^2(t-d)} & \text{if } a \le h(t-d) < b, \\ P_{min} & \text{if } h(t-d) \ge b \end{cases} \quad (15)$$

where the novel boundaries for power allocation can be defined using the expectation and the standard deviation of the feedback CSI: $a = \mathbf{E}[h(t-d)] - 3\sigma$ and $b = \mathbf{E}[h(t-d)] + 3\sigma$ Note the similarity to the definition of $\alpha$ and $\beta$, with the exception of no normalization, leading to $a = \alpha \cdot \mathbf{E}[h(t-d)]$and $b = \beta \cdot \mathbf{E}[h(t-d)]$. $P_{min}$ and $P_{max}$ represent the minimum and the maximum value of the transmit power, respectively. When $h(t-d) < a$ and $h(t-d) \geq b$, the transmission power is set to $P_{max}$ and $P_{min}$, respectively, to prevent resource usages levels from being set too low or too high. $P_{max}$ limits the physical amount of transmit power even if the received CSI is very bad. Using not enough transmit power can result in the system unable to provide users with the desired communication service; hence, the transmit power is set to the minimum power $P_{min}$ even with very good CSI to restrict exploiting unreasonably low transmit power. Between $P_{min}$ and $P_{max}$, power control is performed to ensure channel compensation with the proper transmission power. Subsequently, the different system performances are compared between the default system and the proposed power control system in terms of the channel capacity and the amount of power consumed. The channel capacity based on the controlled transmit power is given by

$$C_{ctrl}(t) = BW \cdot \log_2\left(1 + \frac{h^2(t) \cdot P_{ctrl}(t)}{\rho \cdot BW \cdot N_0}\right). \quad (16)$$

To exploit the delayed feedback CSI in wireless communication systems, including satellite systems, it is necessary to compare the propagation delay with the channel coherence time in the mobile environment. The channel coherence time becomes shorter as the user speed increases because the channel states change quickly, in general, with increased mobility. If the propagation delay is too long and the user has very high mobility, the difference between the current and delayed feedback CSI is too large and the system will not be able to receive correct feedback data within the channel coherence time, thereby inevitably deteriorating the system performance.

Thus, we focus on the cases of $h_{comp}(t) < \alpha$ and $h_{comp}(t) \geq \beta$, which allow to identify the system limitations caused by differences between the delayed feedback and the current CSI and to figure out the inaccurate transmit power control process. The outage probability $p_{out}$ is defined as

$$p_{out} = Pr\left(h_{comp}(t) < \alpha\right). \quad (17)$$

The over-budget probability $p_{over}$ is given by

$$p_{over} = Pr\left(h_{comp}(t) \geq \beta\right). \quad (18)$$

Using the outage and the over-budget probability in (17) and (18), the influence of the delayed feedback CSI can be verified on the system performance depending on the user's mobility and the altitude of the satellite system. In the next section, the performance of a simple transmission power control scheme is analyzed through simulations.

## IV. SIMULATION RESULTS

We now evaluate the system performances of aerial and satellite systems to serve mobile users and verify the possibility of providing reliable throughput at high frequency bands using the OBP system. The impact of the feedback CSI

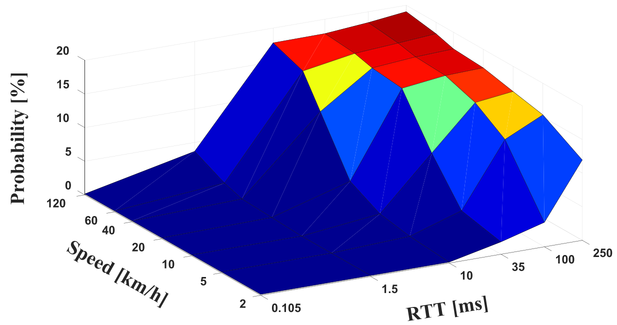


**FIGURE 3. The outage probability with respect to user speed and propagation delay by Lutz's channel model.**

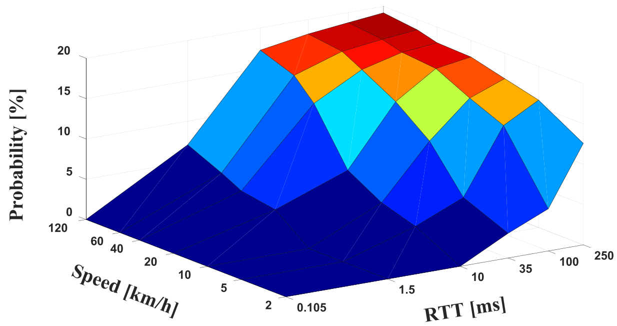


**FIGURE 4. The over-budget probability with respect to user speed and propagation delay by Lutz's channel model.**

is investigated by comparing conditions and altitudes with diverse systems and the limitation of GEO satellite communications is verified with long propagation delays. The outage and the over-budget probability are analyzed quantitatively using (17) and (18), while the transmission power and channel capacity are analyzed using the proposed power control scheme via (15) and (16).

In this scenario, system parameters include propagation delays, user speeds and LOS components. The propagation delays taken into consideration are $t_{prop}$ [ms] = [0.105 1.5 10 35 100 250] to represent the round-trip time of the HAP at an altitude of 17–22 km, LEO satellites at 250–2000 km, MEO satellites at 2000–20000 km, and GEO satellites at 36000 km. The user speeds are $v_{user}$ [km/h] = [2 5 10 20 40 60 120], which express the speeds for walking, biking and travelling via vehicles according to the road conditions. We simulate $m = [1\ 2\ 3\ 4\ 5]$, where $m = 1$ represents the Rayleigh fading channel. The simulation parameters are $P_{min} = 100$ W, $P_{def} = 500$ W, and $P_{max} = 1$ kW for the transmission power. Simulations are performed using the Lutz's LMS and Nakagami fading channels considering user mobility for 20 seconds, and results are averaged over 1000 times per outcome.

In Fig. 3 and Fig. 4 for Lutz's channel model, both the outage and the over-budget probabilities increase to 20 % as the speed and/or propagation delay increase. Fig. 5 and Fig. 6 show the increase of the outage probability, which are as high as 22 % and that of the over-budget probability,

 

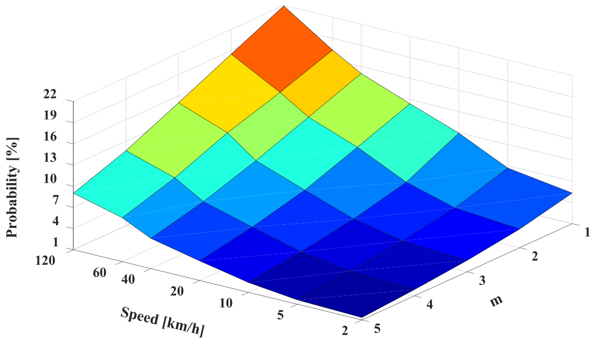


**FIGURE 5.** The outage probability with respect to user speed and LOS component by Nakagami fading channel.

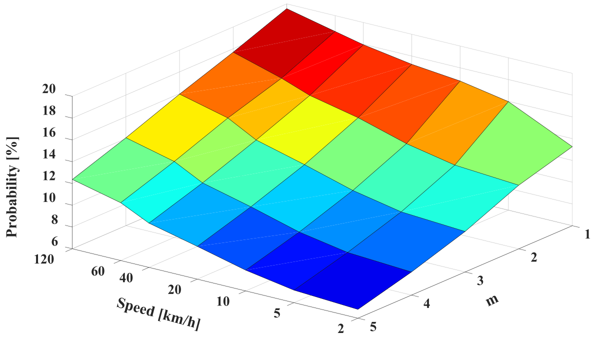


**FIGURE 6.** The over-budget probability with respect to user speed and LOS components by Nakagami fading channel.

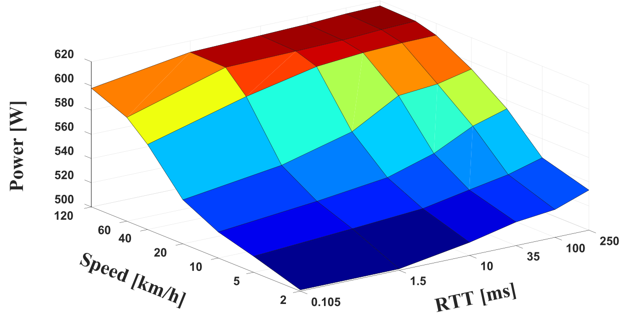


**FIGURE 7.** Average transmission power consumption with feedback CSI for Lutz's channel model.

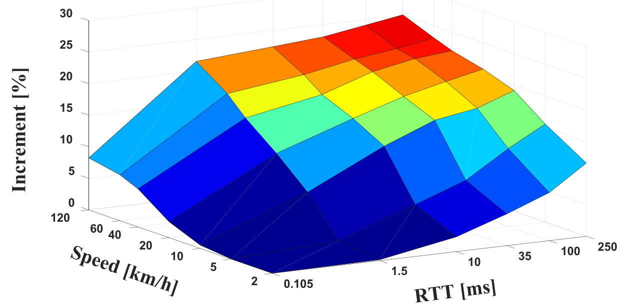


**FIGURE 8.** Channel capacity increments with controlled transmission power for Lutz's channel model.

which increases by 20 %, respectively, as the channel condition worsens and the moving speed increases. The outage and over-budget probabilities represent the condition for insufficient and exorbitant resource usage by channel compensation, respectively. As the environment approaches the GEO satellite condition, the propagation delay becomes much longer than the channel coherence time, deteriorating the accuracy of the delayed feedback system. Above the speed of 20 km/h or the RTT of 10 ms in Fig. 3 and Fig. 4, it can be verified that the system performance degrades sharply. Therefore, high speeds and/or altitudes can be a major cause of system performance deterioration. In addition, it can be seen that the difference between the current and feedback CSI is intensified when the overall channel state is inferior. It is not feasible to use the delayed CSI with the feedback system due to the long propagation delay for the GEO system with the fast time-varying channel and the high user speed. To provide the reliable MSS, new architectures should be devised, such as exploiting SmallSat [54] or CubeSat [55] in addition to utilizing channel adaptation [56] or estimation [57]. On the other hand, in cases of the long-term evolution (LTE) and LTE-advanced technologies, the requirements of maximum latency are up to 10 ms and 5 ms, respectively, and mobility can be served up to 350 km/h. Both systems can reliably service users within the channel coherence time due to the ground infrastructure and the associated relatively short propagation delays [58].

The over-budget case causes excessive resource usage due to the difference between the current and feedback CSI. Then, the average power consumption is calculated with the proposed power control scheme and the channel capacity is analyzed in a comparison with the default system, which uses a fixed amount of transmit power $P_{def}$ to check the performance increments. In Lutz' channel model, Fig. 7 shows the average transmission power consumption with the power control scheme, averaged over 1000 simulations for each moving speed and RTT. At the low speed and with small propagation delay, the average transmit power is similar to $P_{def}$. As the speed and propagation delay increase, the average transmission power consumption grows to 615 W, representing a nearly 23 % increment compared to the default power. Therefore, in order to provide stable services in satellite communications in high speed/frequency environments, assistant or complementary systems are needed. Moreover, in this simulation, the highway environment of clear roads is considered, but numerous actual communication services are deployed in urban environments, which are highly affected by adverse conditions, such as surrounding buildings. If the system environment changes to the urban type, the performance degradation will be more severe and resource usage will increase. Thus, system design efforts for efficient resource use and the performance improvement will be necessary.

In Fig. 8, the channel capacity increments represent the rate of the performance enhancement in terms of the channel capacity with the transmission power control scheme in (16)

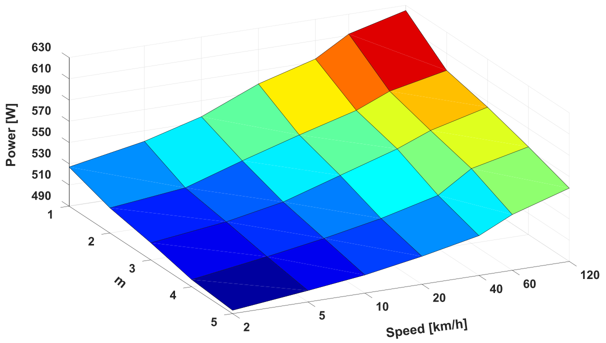


**FIGURE 9.** Average transmission power consumption with feedback CSI for Nakagami model.

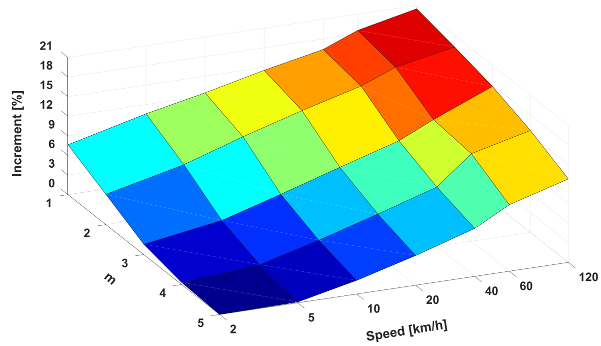


**FIGURE 10.** Channel capacity increments with controlled transmission power for Nakagami model.

normalized by that with the default transmission power. In our scenario, the channel capacity with simple power control based on the feedback information increases from 0.01 to 25 % relative to the default system depending on the environment. The increment of the capacity is large in the conditions characterized by high speeds and long propagation times, however, at the expense of greater power consumption, as shown in Fig. 7, indicating that the power efficiency of the proposed system deteriorates under high speed/frequency conditions. These results verify the feasibility of advancing mobile satellite system performances. Although the system is evaluated with simple power control based on imperfect CSI, the result of capacity increment tends to follow the variation of average power consumptions. This suggests directions for novel MSS systems in the future. It is critical to reduce the propagation delay to enhance the efficiency of transmission power control. The simulation results confirm that the high speed mobile service is very inefficient with GEO satellites; thus, LEO or HAP systems should be exploited as standalone systems to augment higher orbit networks. Additionally, by the resource optimization or system throughput improvement algorithms under power-limited constraints, more efforts should be made to support reliable or stable mobile communication services in satellites with many limitations and vulnerabilities.

In the Nakagami fading model, Fig. 9 shows the averaged power consumption with the proposed power control scheme according to the changes in the LOS component and user speed. With very good channel states ($m = 5$) and low mobility, the resource usage is similar to or less than $P_{def}$ When the channel states become worse and the speed increases, the power consumption increases to 625 W, showing a nearly 25% increase over the default power.

Fig. 10 shows the capacity increments by deploying the power control scheme in (16). The channel capacity with resource control based on the feedback CSI increases from 0.01 to 21 % relative to the default system without power control. Under good channels ($m =$ 4 or 5) and low mobility, the proposed system achieves better performance than the default system even with a lower or similar power consumption level. However, at high speeds and with a bad channel state ($m =$ 1), the system requires more resources compared to the performance enhancement.

Through these results, the system performance can be verified according to the LOS components and user speeds. The system must consider the aforementioned scheme for propagation reduction and should ensure more elaborate CSI utilization to support the environments with fewer dominant LOS components. In simulation results under good channel conditions, it can be confirmed that the capacity increments follow the increasing average power usage, similar to the results of the LMS channel. Accurate channel information is vital for better performance. It is necessary to develop novel channel estimation or compensation technologies for more accurate channel information on the satellite board, so that the system can provide appropriate resource allocation and throughput support according to channel conditions.

## V. CONCLUSION

In this paper, the conventional and general channel models of satellite systems were analyzed in the mobile environment, and a simple transmission power control method was evaluated based on the delayed feedback CSI. The performance degradations were confirmed due to an increase in the frequency band from 2 GHz to 20 GHz and higher user speeds both in highway and urban environments. Especially, more severe degradation was observed with a change in the frequency band as compared to that on a road environment. In addition to the carrier frequency change as the greatest cause of the degradation, we focused on mobility, which causes an additional performance reduction.

A simple power control scheme with the channel compensation method was also applied to investigate the impact of the propagation delay and the amount of LOS components. The potential of the system was examined to assure stable performance and to mitigate degradation from mobility based on the feedback system. The performance was analyzed in terms of the outage and over-budget probabilities, which represent the gap of the channel compensation information between the current and feedback channels. The outage probability represents underused resource and shows performance degradation due to insufficient power. The over-budget probability denotes the overused power that indicates the inefficiency of resource utilization. Consequently, as the propagation delay and mobility increase, both probabilities grow by 20 % for Lutz's channel model, and the outage and over-budget probabilities of the Nakagami model also increase by 22 % and 20 %, respectively, as the channel worsens and mobility increases. Above the speed of 20 km/h and the propagation delay of 10 ms, it could be verified that the results of both metrics increased rapidly as long propagation delay and rapid movements increased an inefficient use of resources due to the deterioration of the communication environments. The system performance with the power control method was analyzed using the average power consumption and channel capacity increments. Simulation results show the capacity enhancement up to 25 % with high speeds and propagation delays compared to the default system for Lutz's channel model. Simulation results for performance evaluation with Lutz's model show more influence from user mobility (speed) than from the RTT for satellite and aerial systems. In addition, it could be verified that the performance increment was in general larger than the resource consumption, while in the case of bad channel states, the amount of power consumption was very high compared to the capacity increase for performance evaluation with the Nakagami fading model.

Despite the capacity improvement, it could be seen that power efficiency decreases due to the greater amount of power used, by up to 23 %. Although the power control scheme was very simple, results showed that system performance and resource use at the low altitude were comparable to those of the default system. On the other hand, systems in high speeds and altitudes have great difficulty in overcoming the physical conditions and providing reliable communication services with a simple scheme. To improve the performance of satellite communications with mobility based on the delayed CSI, the system should be able to perform more complicated techniques, such as minimum mean square error-successive interference cancellation (MMSE-SIC) in conjunction with the feedback system.

In the future, one can consider utilizing aerial platforms in satellite standalone systems so as to ensure the stable performance by mitigating the impact of long propagation delays in the mobile environment. For example, to provide better performance in the conventional satellite system, the system development via HAP as an intermediate node can be exploited to construct an emergency network rapidly.

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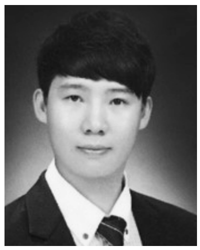

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