Rate and Outage Probability In Dual Band Systems With Prediction-Based Band Switching

Daoud Burghal, Student Member, IEEE, and Andreas F. Molisch, Fellow, IEEE

Abstract—5G cellular systems will have the ability to communicate in either centimeter-wave or millimeter-wave bands, though not necessarily in both bands simultaneously. Therefore, techniques to optimize switching between those bands are needed. In this paper, we propose a suitable scheme based on rate prediction. Specifically, in each time-frame the base-station predicts the state of large-scale fading for the next time-frame; data transmission is then carried over the band that is anticipated to achieve the larger data rate. We analyze the scheme based on the assumption that large-scale fading is lognormally distributed and with a finite correlation between the two bands.

Index Terms—Band selection, band switching, dual band, dual mode, millimeter wave, out-of-band.

I. INTRODUCTION

Usage of the millimeter-wave (mm-wave) frequency band will help to satisfy the continuously increasing demand for wireless data. Although the large bandwidth at the mm-wave band provides an opportunity for high data rates, its harsh propagation environment degrades the reliability and quality of service in number of scenarios, by intermittent connectivity of the mobile station (MS). Due to this reason, as well as requirements for backward compatibility, next generation wireless networks are anticipated to use both centimeter-wave (cm-wave) band and mm-wave frequency bands [1], [2]. Thus, recently developed systems incorporate the two frequency bands to serve different applications and to adapt to different environments. Such dual-band systems can combine the advantages of both bands, i.e., large throughput at mm-waves and better reliability at cm-waves. Yet, simultaneous usage of the two bands might not always be possible or desirable, e.g., due to crosstalk, or limits on the baseband processing. Thus, finding suitable switching strategies is essential.

Recent field studies suggest that various aspects of the propagation channel in the two bands are correlated [3]–[5]. In this work we investigate how the base-station (BS) can utilize the correlation of large scale fading to predict the channel state in future time-frames, and select the band that provides the larger predicted rate in it.

Switching in dual band systems is a relatively new problem, nevertheless, a number of recent studies considered the interplay between cm-wave and mm-wave bands. Refs. [3], [4], [6] utilize the angular correlation in the two bands to provide an estimate of the Angle of Arrival at mm-waves, from cm-wave measurements, which can reduce beamforming complexity. Furthermore, [4] suggests to use both frequency bands for data communication, and proposes a two queue model to assign data to each band such that delay is minimized and throughput is maximized. Ref. [7] considers the downlink resource allocation in a small-cell network where the BS aims to assign the MS or services to the resources in the two bands.

Different from above, we consider the correlation of channel states to select the data communication band. The contribution of this work is twofold: (i) propose a dual band model and switching scheme based on large scale fading prediction, and (ii) based on Gaussian distribution assumption and a proposed correlation model, we analyze the achievable rates and outage probabilities.

II. SYSTEM MODEL

To focus on the basic switching problem, we consider a single link to a mobile device in a time slotted cellular system in a stationary environment. More advanced scenarios, such as moving blockers, are left for future work. Both the BS and the MS can operate in the cm-wave and mm-wave frequency bands, with center frequencies $f_c$ and $f_m$, respectively. Due to practical limitations of the MS, we assume that it operates in a single frequency band at a time. The BS controls the band selection process: given the channel conditions in the current and the previous time instances the BS predicts the future channel conditions and thus chooses the band that may result in the larger data rate.

It is well established that the small scale fading in the two bands is independent due to the large frequency separation; furthermore, modern diversity techniques mostly eliminate its impact [8]. Thus, we focus on the large scale fading, since it varies relatively slowly over time and maintains time and frequency correlation, making it suitable for prediction-based band switching. We define a time-frame as a sequence of $L$ time slots (data units), such that the BS makes the band switching decision at the end of each time-frame. During each time-frame the MS observes the channel condition based on the received data or through a passive observation of the beacon signals frequently transmitted by the BS in both bands. At the end of each time-frame the MS averages the observed channel states to eliminate the impact of residual small scale fading and feeds back this information to the BS. We assume that the MS can frequently observe the channel state in the other band during the frame; note that this is no contradiction to the assumption that data communication is carried over.
a single frequency band at a time, since the MS only needs to observe the received power, sensing in the RF domain would be one simple way of easily obtaining the required information. Fig. 1 provides an illustrative example. For instance if $\hat{S}_t$ and $S^{b}(t+1)$, which are random processes

$$\sigma^2_b = \text{Var}(S^b(t)), \quad \text{for } b \in \{c, m\}$$

are jointly normal. As a consequence, noting that $E\{\alpha^b_{T} S_t\} = 0$, to describe the joint distribution of the prediction values it is enough to characterize the covariance matrix

$$\text{Cov}(\alpha^b_{T} S_t, \alpha^{b'\top} S_{t'}) = \mu_b^\top U_S^{-1} \text{Var}(S_t) U_S^{-1} \mu_{b'} = \mu_b^\top U_S^{-1} \mu_{b'}.$$  

We also assume that the correlation between different time-frames decreases fast, so that the time average can be replaced with expectation. Next, we give an example of such a correlation function, then we analyze the expected rate and the outage probability of the scheme.

### A. Correlation Model

Although not used in the analysis, for completeness, we discuss a possible correlation model. Typically, for large scale fading the correlation between two points follows

$$\text{Cov}(S^b(\tau_1), S^{b'}(\tau_2)) = \exp\left(\frac{-|d_{\tau_1} - d_{\tau_2}|}{\delta_{\text{decor}}} \times \log(2)\right) \sigma^2_b,$$

where $\delta_{\text{decor}}$ is the decorrelation distance in band $b$. Assuming that the two bands are correlated and have a correlation coefficient, $\rho_{c,m}$, with an absolute value that is non-increasing function of frequency.
separation, \( \rho_{c,m} = \rho(f_c - f_m) \in [-1,1] \), we propose a correlation value over time and frequency that generalizes the model above and maintains consistency

\[
\text{Cov}(S^b(\tau_1), S^b(\tau_2)) = \rho_{b,b'} \sqrt{\text{Cov}(S^b(\tau_1), S^b(\tau_2))} \times \\
\sqrt{\text{Cov}(S^b(\tau_1), S^b(\tau_2))}.
\]  

(7)

**B. Rate**

We first start by deriving the approximate average rate of the genie-aided scheme, then derive a lower bound.

1) **Approximate rate of the genie-aided scheme:** Following the discussion in Sec. III, an optimal scheme, in which a genie informs the BS of the true channel state in the upcoming frame, would choose band \( b' \) over \( b \) if \( R^b > R^{b'} \), thus the expected rate \( \bar{R}_b \triangleq \mathbb{E}\{ R_b \} = \mathbb{E}\{ \max(R^r, R^m) \} \), where the expectation is over all channel realizations, or equivalently all times, thus the time index is omitted from the left hand side. Using the high SNR assumption, we can approximately write the rate in band \( b \), as

\[
R^b(t+1) = \omega_b \log(\gamma_b^{10} S^b(t+1)),
\]

with this we redefine the rates at \( t+1 \) and write

\[
\bar{R}_b \approx \mathbb{E}\left\{ \max\left( \tilde{R}^r(t+1), \tilde{R}^m(t+1) \right) \right\}.
\]

Since \( S^b \) is normally distributed with zero mean, with basic manipulations we note that \( \bar{R}^r \) is also normally distributed with a mean and a variance, respectively,

\[
\bar{\mu}_b = \omega_b \log(\gamma_b), \quad \bar{\sigma}_b^2 = \left( \omega_b \gamma_b^{10} \log(10) \right)^2 \sigma_b^2,
\]

i.e., \( \bar{R}_b \) is approximately equal to the expected value of the maximum of two jointly normal random variables. Using a result from [11], with \( \Delta = \bar{\mu}_c - \bar{\mu}_m \), we have

\[
\bar{R}_b \approx \bar{\mu}_c \Phi(\frac{\Delta}{\theta}) + \bar{\mu}_m \Phi(\frac{-\Delta}{\theta}) + \theta \phi(\frac{\Delta}{\theta}),
\]

(9)

where \( \phi \) and \( \Phi \) are the PDF and the CDF of the standard normal random variable \( \Phi \), respectively, and \( \theta \) is given as

\[
\theta = \sqrt{\bar{\sigma}_c^2 + \bar{\sigma}_m^2 - 2 \rho_{c,m} \bar{\sigma}_c \bar{\sigma}_m}.
\]

With \( \Phi(-x) = 1 - \Phi(x) \), the first two terms in (9) represent a convex combination of the means, \( \bar{\mu}_b \), while this might decrease the average rate (compared to the rate of a single band), the last term in (9) increases its value. In fact, compared to maxs \( \bar{\mu}_b \), one might show that the gain in the rate, which can be written as \( \theta \phi(\frac{\Delta}{\theta}) - |\Delta| \Phi(\frac{-\Delta}{\theta}) \), is an increasing function of \( \theta \), which in turn is an increasing function of \( \bar{\sigma}_b \) and a decreasing function of \( \rho_{c,m} \). Thus, we expect to notice a gain of using the two bands when the shadowing variance is large and correlation is small.

2) **Lower bound for rate of the scheme:** To derive a lower bound on the scheme rate, we first note that we can write the rate in next time-frame as

\[
R_s = R^r 1_{(\hat{r}_c > \hat{r}_m)} + R^m 1_{(\hat{r}_m > \hat{r}_c)},
\]

(10)

where \( 1_{(\hat{r}_m > \hat{r}_c)} \) is an indicator function that takes value one if \( \hat{r}_m > \hat{r}_c \). Noting that the result would depend on the observed values of \( S_t \), to avoid using the empirical average, average over time, we assume a fast decaying correlation function as discussed above, so we can use the expectation instead. With the iterated expectation we have

\[
\mathbb{E}\{ R_s \} = \mathbb{E}\{ \mathbb{E}\{ R^c | S_t \} 1_{(\hat{r}_c > \hat{r}_m)} + \mathbb{E}\{ R^m | S_t \} 1_{(\hat{r}_m > \hat{r}_c)} \}.
\]

Since evaluating \( \mathbb{E}\{ R^b | S_t \} \) is difficult, and noticing that \( R^b \) is a convex function of \( S^b \), we take the expectation inside \( R^b \) to find a lower bound. Then with the joint normal assumption we have [9]

\[
\mathbb{E}\{ S^b | S_t \} = u_b^T U_S^{-1} S_t = \alpha^T S_t.
\]

Plugging the above to the rate equation (2), and noticing the similarity to the predicted rates we have

\[
\mathbb{E}\{ R_s(t+1) \} \geq \mathbb{E}\{ \max\{ R^m, R^r \} \}. \tag{11}
\]

To evaluate the above we can use the high SNR approximation here as well. Then we have \( \bar{R}_b \approx \omega_b \log(\gamma_b^{10} \alpha^T S_t) = \omega_b \log(\gamma_b) + \omega_b \log(10) \alpha^T S_t \), which is normally distributed with mean

\[
\mu_{p,b} = \omega_b \log(\gamma_b) + \omega_b \log(10) \mathbb{E}\{ \alpha^T S_t \} = \omega_b^0 + \omega_b^0 \mathbb{E}\{ \alpha^T S_t \} = \omega_b^0,
\]

where we used the fact \( \mathbb{E}\{ \alpha^T S_t \} = 0 \). The variance is

\[
\sigma_{p,b}^2 = \omega_b^0 \text{Var}(\alpha^T S_t) = \omega_b^0 \sigma_{u^T}^2 U_S^{-1} u_b.
\]

Similar to (9), we have

\[
\mathbb{E}\{ R_s \} \gg \mu_{p,c} \Phi(z) + \mu_{p,m} \Phi(-z) + \theta \phi(z),
\]

where \( z = \frac{\mu_{p,c} - \mu_{p,m}}{\sigma_{p,c}} \), \( \theta_p = \sqrt{\sigma_{p,c}^2 + \sigma_{p,m}^2 - 2 \nu_p} \), and

\[
\nu_p = \text{Cov}(\omega_{p,c}^T S_t, \omega_{p,m}^T S_t) = \omega_{c,m}^T \omega_{c,m}^T U_S^{-1} u_m.
\]

As discussed above, we anticipate a rate improvement with increasing \( \theta_p \), however, since \( \sigma_{p,c} \) and \( \nu_p \) are functions of \( \rho_{c,m} \) it is not possible to have a straightforward interpretation of its impact. We expect a trade-off, as low values of \( \rho_{c,m} \) reduce the correlation and thus the quality of prediction yet improve the diversity of channel states.

**C. Outage probability**

We next provide ways to calculate the outage probabilities for the genie-aided and the proposed schemes.
1) Outage probability for the genie-aided band selection: Choosing the band that has the largest instantaneous rate in each frame will result in the smallest outage probability. For a given threshold rate $R_T$ we have

$$
\mathbb{P}(R_g \leq R_T) = \mathbb{P}(\max(R^c, R^m) \leq R_T) = \mathbb{P}(R^c \leq R_T, R^m \leq R_T) = \mathbb{P}(\omega_c \log(1 + \gamma^c \omega^c) \leq R_T, \omega_m \log(1 + \gamma^m \omega^m) \leq R_T) = \mathbb{P}(S^c \leq S_{T,c}, S^m \leq S_{T,m})
$$

where the constants $S_{T,c}$ and $S_{T,m}$ follow

$$
S_{T,b} = \frac{1}{\gamma^b} \log_{10}\left(\frac{\exp\left(\frac{R_T}{\omega_b}\right) - 1}{\gamma^b}\right).
$$

As above, assuming that $S^c$ and $S^m$ are jointly normal, we can evaluate that probability exactly.

2) Outage probability for the proposed scheme: Starting from (10) and using the assumption that the correlation of the shadowing samples decays relatively fast, the average outage probability is given as follows

$$
\mathbb{P}(R_g \leq R_T) = \mathbb{P}(R^c \leq R_T, R^c \geq \bar{R}^c) + \mathbb{P}(R^m \leq R_T, R^m \geq \bar{R}^m)
$$

where we observe an order of magnitude improvement. In mid-range distances, especially for the outage probability to “mm-wave only” at short distances (with an outage of the mm-wave band, in a non gene-aided system, could degrade the outage probability compared to a “cm-wave only” system for small $R_T$ values.

V. SIMULATION

We consider a system that implements communications in two frequency bands, cm-wave with $f_c = 2.4$ GHz and $\omega_c = 10$ MHz, and mm-wave with $f_m = 27$ GHz and $\omega_m = 100$ MHz. Correlation between the shadowing at two bands follows (7), with $\rho_{c,m} = 0.6$, and decorrelation distances $d_{\text{cor}}^c = 18$ m and $d_{\text{cor}}^m = 13$ m. The shadowing standard deviations are $\sigma_c = 5$ dB and $\sigma_m = 7$ dB. We use a break point pathloss model, [8], with $d_{\text{break}} = 30$ m and propagation exponent $\epsilon = 4$ after the break distance for both bands. We assume that the EIRP (Equivalent Isotropically Radiated Power) is equal to 15 dBm for both bands. For simplicity and to interpret the results, we assume that the MS moves on a circle around the BS and it reports the average SNR every 5 m. The prediction of the channel state is done with $q = 5$. We run Monte Carlo simulations over $10^5$ realizations. Fig. 2 shows (a) the achievable rates and (b) the outage probabilities. In both subplots, the proposed scheme shows a similar behavior to “mm-wave only” at short distances (with an outage rate trade-off), and similar behavior to “cm-wave only” at large distances. They also show clear improvement in mid-range distances, especially for the outage probability where we observe an order of magnitude improvement. In general, based on our band selection criterion, the rate is maximized at all distances. While the outage at small distances is larger than for a pure cm-wave system, the actually achieved values (better than $10^{-2}$) are well within the target values of cellular systems.

REFERENCES


