Analyzing Diurnal Variations of Millimeter Wave Channels

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***Abstract*—5G is planning to exploit millimeter wave (mmWave) channels to achieve the massive capacity increase needed for future applications. Unfortunately, wireless signal attenuation and noise in this high frequency band is very sensitive to atmospheric conditions, such as temperature and humidity. Given that such atmospheric conditions at any given location could vary throughout the day, mobile communication systems seeking to exploit this band must expect some sort of diurnal variations in attenuation and noise. In this paper, we study the extent of diurnal variation in mmWave channels in three largest cities of Australia by accessing the hourly air quality and weather data over 12 months in 2015. We find that all planned mmWave bands, with the exception of 60 GHz, experiences significant diurnal variation in attenuation and noise. The attenuation and noise generally drops in the middle of the day when temperature rises and humidity falls, but remains high during the night. The diurnal variation is found to be more significant in summer compared to winter. The 60 GHz band remains stable throughout the day as this band is mainly affected by the amount of oxygen in the air, which does not fluctuate much for a given location.**

I. Introduction

One of the main differences 5G is going to bring over 4G is the massive increase in channel capacity and data rates. To achieve this, very high frequency spectrum in the range of 30 to 300 GHz, which is also known as millimeter wave (mmWave), will be used. A key difference between existing wireless communication at lower frequencies and mmWave is that the water (H_2O) molecules in the air, which can absorb signal energy at a very high rate if excited, have their natural resonance frequencies within the mmWave band. This means that the mmWave band is very sensitive to the amount of water (humidity, moister, or rain) in the air. Because of this, there are different channel models recommended for different weather conditions [5], [6], [7], [21], [22], [27].

Interestingly, resonating water molecules not only absorb signal energy causing attenuation, they also re-radiate some of the absorbed energy leading to increased noise at the receiver. This type of molecule-induced noise is often referred to as *molecular noise* [8], [11], [12]. It has been argued that as conventional *thermal* noise in the receiver is expected to decline with improvements in hardware technology, molecular noise may become the dominant source of noise for the mmWave and beyond [11]. Consequently, presence of water molecules in the air will not only affect signal attenuation, but also the overall noise at the receiver. Finally, as the severity of molecular absorption is also sensitive to air temperature, any variation in temperature-humidity will directly affect attenuation and noise in mmWave band.

Given that temperature and humidity at any given location could vary throughout the day, 5G communication services seeking to exploit this band must expect some sort of diurnal variations in attenuation and noise even during clear weather. Although there has been extensive studies in the literature to characterize mmWave channels under difficult weather conditions, such as rain, fog, or snow [21], [27], little has been reported on any potential issues during clear days. To build a successful 5G mm-wave based network, channels for mm-wave systems must be understood under all conditions, including clear days.

The aim of this paper is to understand the extent of diurnal channel variations that could be expected for mmWave-based 5G channels during clear days in typical cities around the world. To achieve this, we apply well known molecular absorption models to the hourly air quality and weather data over 12 months in 2015 collected in three largest cities in Australia. We find that even if there is no rain, there can be significant diurnal variation in both attenuation and noise between two communicating devices separated by a fixed distance. The attenuation and noise generally drops in the middle of the day when temperature rises and humidity falls, but remains high during the night. The diurnal variation is found to be more significant in summer compared to winter. This observation is valid for all bands within mmWave except for the 60 GHz band, which remains very stable through the day. This is due to the fact that 60 GHz is mainly affected by the amount of oxygen in the air, which remains relatively stable despite fluctuations in temperature and humidity.

The rest of the paper is structured as follows. The molecular absorption model used to calculate attenuation and noise is reviewed in Section II. Details of the air quality data are described in Section III. Section IV analyzes diurnal channel variations by applying the molecular absorption model to the air quality data. We conclude the paper in Section V.

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II. Molecular Absorption Model

The molecular absorption model defines how different species of molecules in the communication channel absorb energy from the electromagnetic signals and how they re-radiate them back to the environment. This section first explains the concept of *absorption coefficient* used to characterize the absorption capacity of a given molecule species, followed by the attenuation and noise models that build on this coefficient.

A. Molecular absorption coefficient

The effect of a given molecule, S_i on the radio signal is characterized by its molecular absorption coefficient at frequency f, $K_i(f)$ which varies with pressure and temperature of the environment as well. The molecular absorption coefficients of many chemical species for different pressure and temperature are available from the publicly available databases such as *HITRAN* [10] and *NIST Atomic Spectra* [4]. Nevertheless, the atmospheric air is a mixture of different gases and as we will see in Section III, the mixing ratio of its constituent gases may change in hourly basis. The pressure and temperature of the air is also variable. We therefore need to take these variation into account. In order to model these variations, we assume the mmWave radio channel is a medium consisting of N chemical species $S_1, S_2, ..., S_N$ and $m_i(t)$ is the mole fraction per volume, i.e., mixing ratio of molecule S_i in the medium at time t. We further assume that the temperature and pressure of the medium at time t is $\mathcal{T}(t)$ and $\mathcal{P}(t)$. The *medium absorption coefficient*, $K(t, f)$, at time t and frequency f is therefore a weighted sum of the molecular absorption coefficients in the medium [17], [26]:

$$K(t, f) = \sum_{i=1}^{N} m_i(t) K_{i,t}(f) \tag{1}$$

where $K_{i,t}(f)$ is the molecular absorption coefficient of species S_i in the given temperature, $\mathcal{T}(t)$ and pressure $\mathcal{P}(t)$ that can be obtained from HITRAN [10] and NIST [4].

B. Attenuation

The attenuation of the radio signal at the mmWave frequencies is due to spreading and molecular absorption [20]. The total attenuation at time t , frequency f and a distance d from the radio source, $A(t, f, d)$ is:

$$A(t, f, d) = A_{\text{spread}}(f, d) \times A_{\text{abs}}(t, f, d) \tag{2}$$

where A_{spread} and $A_{\text{abs}}(f, d)$ are respectively, the attenuation due to spreading and attenuation due to molecular absorption at time t , frequency f and a distance d from the radio source. The spreading attenuation is given as [25]:

$$A_{\text{spread}}(f, d) = \left(\frac{4\pi f_0 d}{c}\right)^2 \tag{3}$$

where f_0 is the central frequency and c is the speed of light and f_0 is the central frequency. The attenuation due to molecular absorption is given as [20], [16]:

$$A_{\text{abs}}(t, f, d) = e^{k(t,f) \times d} \tag{4}$$

where $K(t, f)$ is the absorption coefficient of the medium at time t and frequency f in m^{-1} and d distance in m. Many linear approximations for equation 2 have been proposed in the literature for different frequencies (in dB or dB/Km) [19]. The ITU Radio communication Sector (ITU-R) also provides various procedures to estimate specific attenuation due to the dominant molecules in the air (O_2 and H_2O) [5] which both can be easily derived from equations 3 and 4.

C. Noise

The receivers usually encounter with few types of noises including the thermal noise (N_{Thermal}) generated by the thermal agitation of the charge carriers; electronic noise (Elec) from receiver input circuits and ambient noise from the environment. The ambient noise in the higher frequencies channel is mainly originated by the molecular absorption noise (N_{abs}) which is due to re-radiation of the absorbed energy by the molecules in the channel [8], [11]. The total noise power at the receiver therefore is:

$$N_{\text{mmWave}} = N_{abs} + N_{\text{Thermal}} + N_{\text{Elec}} + N_{\text{Others}} \tag{5}$$

where N_{Others} is the noise from other probable sources. N_{thermal} and N_{Elec} depend on the receiver's technology in use. The thermal noise for a mmWave receiver with 2GHz bandwidth at temperature of 21°C is around -84 dBm. However, there are some promising evidences that point to the future generation of antenna (such as Graphene-based transceivers) which has a very low thermal noise that means molecular noise is expected to be the dominant source of noise in future nanomaterial-based receiver systems [11].

The molecular absorption noise has been studied in the literature since 1986 when F. Box proposed a model for sky atmospheric noise for frequencies higher than 18GHz [12]. There are a number of works that have studied the atmospheric noise for mmWave frequencies such as [24] which experimentally measured the atmospheric noise variation in Mauna Kea in Hawaii over many night and days using a 143 GHz and 268 GHz transmitter. Recently the molecular noise has been re-considered for higher frequencies such as terahertz band ranging from 0.1-10 THz [11], [8]. Molecular absorption is not white and its power spectral density (PSD) is not flat because of the different resonant frequencies of each type of molecules. The PSD of the molecular absorption noise that affects the transmission of a signal, $S_{N_{abs}}$, is contributed by the atmospheric noise, S_N^B and the self-induced noise, S_N^X as [12], [23]:

$$S_{N_{abs}}(t, f, d) = S_N^B(f, d) + S_N^X(t, f, d) \tag{6}$$

$$S_N^B(f, d) = lim_{d\to\infty}(k_B T_0(1 - e^{-K(f)d}))\Big(\frac{c}{\sqrt{4\pi} f_0}\Big)^2 \tag{7}$$

$$S_N^X(t, f, d) = P(f)(1 - e^{-K(t,f)d})\Big(\frac{c}{4\pi d f_0}\Big)^2 \tag{8}$$

where $K(t,f)$ is the absorption coefficient of the medium at time t and frequency f, f_0 is the central frequency, T_0 is the reference temperature ($296K$), k_B is the Boltzmann constant, $P(f)$ is the power spectral density of the transmitted signal and c is the speed of light. The total noise power at the receiver in Watt can be obtained by integrating the Equation 8 over the receivers bandwidth.

III. Air Composition and Atmospheric Data

The major elements of the atmospheric air are nitrogen (78%), oxygen (about 21%) and other gases such as argon, helium, neon and carbon dioxide (totally less than 1%) [13]. Water in the form of moisture also exists in the air which is highly variable, more commonly ranging from 0.2-3%. Ambient air composition also is affected by the air pollutants mainly ozone (O_3), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), CO and particulate matter (PM), a general term that used for a mixture of solid particles and liquid droplets suspended in the air [15]. PM is characterized according to size, $PM_{2.5}$ and PM_{10} stand particles that are less than or equal to 2.5 and 10 microns in diameter, respectively.

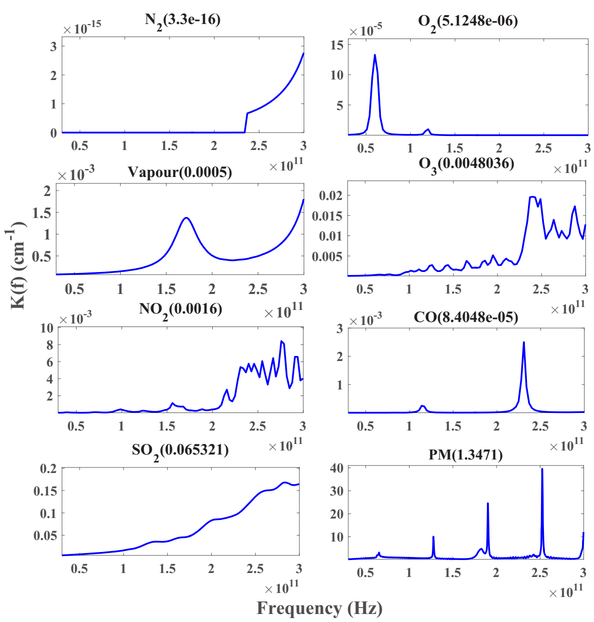
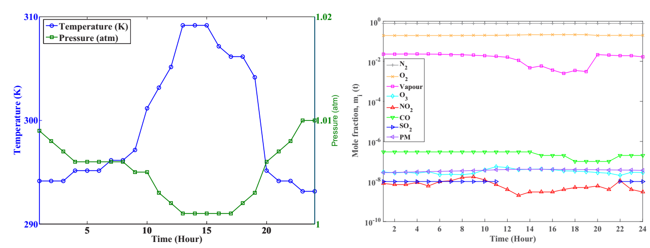


Fig. 1: Absorption coefficient of the main constituent element of the normal air.

Figure 1 shows the absorption coefficient of the main constituent species of the normal air over 30-300 GHz[1]. The average absorption coefficient over 30-300 GHz for each molecule has been mentioned in its title. While the absorption of the nitrogen is almost zero, PM, SO_2 and O_3 have the highest absorptions, respectively with 1.3, 0.06, 0.005 cm^{-1}. The molecular absorption of few constituent gases over mmWave frequencies are almost zero that includes argon, helium, neon and carbon dioxide [4].

While the concentration of the main air components (nitrogen and oxygen) are almost constant, the concentration of some components such as water vapor and air pollutants are variable depend on location, time and atmospheric conditions, i.e., temperature and pressure. The air quality station in the cities (such as the one for Sydney [1]) provides hourly air quality data that includes concentration of: Ozone O_3 in pphm[2], nitrogen dioxide NO_2 in pphm, carbon monoxide CO in ppm[3], sulfur dioxide SO_2 in pphm and particles PM_{10} and $PM_{2.5}$ in $\mu g/m^3$. Since in equation 1 the molar fractions (relative amounts) of these gases in the air are used to calculate the absorption, all the values need to be converted to the relative amount. ppm and pphm are in the ratio form where $1ppm = 0.0001\%$ of mole ratio [18]. To calculate the equivalent molar fraction of $\mu g/m^3$, the ideal gas law, $P_p = \frac{nRT}{V}$, is used where P_p is partial pressure of selected gas, $\frac{n}{V}$ is absolute gas concentration in *mole per volume*, T is temperature in *kelvin* and R is the ideal gas constant [4]). By using the Dalton's law [14], mole fraction will be partial pressure to the total pressure ratio.



(a) Temperature/pressure (b) Mole fraction variation, $m_i(t)$

Fig. 2: Atmospheric variation (air composition, pressure and temperature) in Sydney/Rozelle weather station on 11 of Dec 2015.

In order to analyze the mmWave channel, the variation of water vapor mole fraction and atmospheric conditions including temperature and pressure also are required. The last two not only are required to convert gas concentration to mole fraction but also are used to extract absorption coefficients from available databases. This supplementary data have been provided through online available weather databases such as [2], [3]. The amount of vapor in the ambient atmosphere in these databases are presented in form of relative humidity. Relative humidity is the ratio of the partial pressure of water vapor to saturation vapor pressure at the same temperature. The saturation vapor pressure (P_s) in pascal can be achieved by $P_s = 610.78 \times \exp\left(t/(t+238.3) \times 17.2694\right)$ [9] where t is temperature in $^\circ C$. Our data also include the oxygen mole

[1] There is no absorption coefficient for PM in HITRAN and NIST. Instead, as PM in Sydney are mainly composed of organic matters (46%), sea salt (20%), inorganic aerosol (15%), dust (9%) and elemental carbon (10%) [15], we use the absorption coefficient of available inorganic matters (HNO_3, NH_3), organic matter (CH_4) and chloride species (NCL, HOCL, CH_3CL) to approximate the absorption coefficient of PM in Sydney.

[2] parts per hundred million

[3] parts per million

[4] $8.314J/mol$

fraction which is almost constant in dry air (20.946%). For moist air, we derive oxygen mole fraction from moisture mole fraction using Dalton's law [18]. As stated earlier, we consider only clear days.

Figure 2b presents our collected data for one station in a particular date (Sydney, Rozelle on 11 Dec 2015) which includes the mole fraction of the main constituent components of the air. While mole fraction of oxygen is almost steady, water vapor as the other important component varies significantly. The corresponding temperature-pressure also is presented in Figure 2a for the same day and location which shows that the temperature and pressure vary respectively by 16°C and 10 hPa (0.0001 atm) during 24 hours.

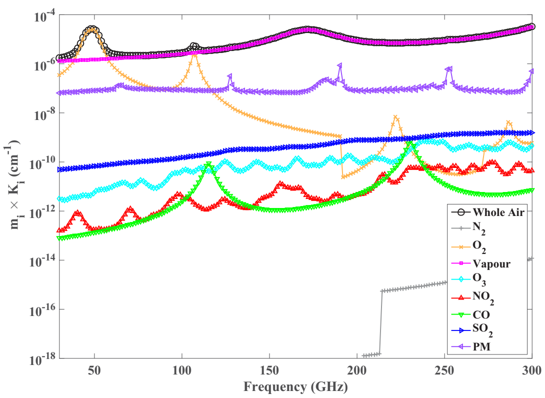


Fig. 3: Absorption spectrum of the normal air (black curve marked by circles) and the contribution of its constituent elements ($m_i \times K_i(f)$) in atmospheric temperature/pressure of 21°C/1.009 atm.

Figure 3 shows the overall absorption coefficient of the Sydney Rozelle air over frequency range of 30 to 300 GHz at 1am (11 Dec 2015) which has been calculated from equation 1 using the mole fractions of time equal to 1am, extracted from Figure 2b. We also show the contribution of each individual constituent gas in the total absorption of the medium ($m_i \times K_i(f)$). As it can be seen, the water vapor and oxygen are the main effective molecules. Particulate matters, O_3 and SO_2 are the next contributers and the N_2 has the lowest contribution.

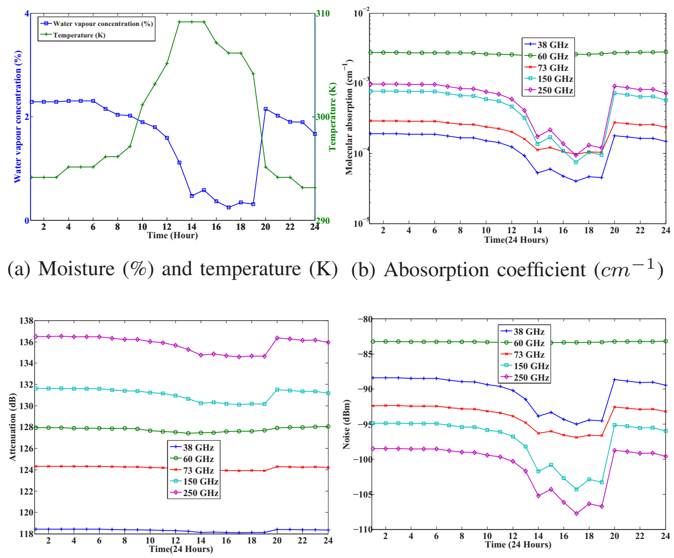
In the next section, we show how fluctuation in atmospheric conditions can cause variation in mmWave communication channel.

IV. Evaluation of Diurnal Channel Variation

In this section, we apply molecular absorption model to hourly air quality data from different cities to study the diurnal variation of attenuation and noise in mmWave channels.

A. Methodology

We consider the three largest Australian cities, Sydney (Rozelle and airport), Melbourne (airport) and Brisbane (airport). We study each location over all months in 2015. For each location/day, we follow the procedure of Section III to extract hourly data for temperature, pressure and air composition from the corresponding air quality station located around that location. For each particular location/date/hour, we then extract the absorption coefficient of the constituent molecules for the given pressure and temperature of that hour. Finally, using the channel model explained in Section II, we calculate the absorption coefficient, attenuation and molecular noise for the five frequency windows, 38, 60, 73, 150 and 250 GHz each with 2GHz width, that have been mentioned in the literature as the most promising mmWave channels due to their lowest absorptions [21].



(a) Moisture (%) and temperature (K) (b) Abosorption coefficient (cm^{-1})

(c) Attenuation(dB) (d) Molecular Noise (dBm)

Fig. 4: Diurnal channel status in Sydney (Rozelle) on 11 Dec 2015.

B. Results for Sydney

First, we present the results for one city, Sydney (Rozelle station on 11 Dec 2015) for a fixed distance of 400m assumed between two mmWave devices to gain insight to diurnal variations of weather and its impact on channel performance. Figure 4a shows that the moisture varies between 0.2% and 2.3% and the temperature varies between 20° C and 36° C throughout the day. Figure 4b, 4c and 4d show the impact of temperature and humidity variation on channel quality over the five mmWave sub-bands.

We make an interesting observation. The channel quality varies noticeably during the day over all selected mmWave sub-bands, except for 60 GHz, as the molecular absorption (Figure 4b) changes by a factor of 6 on average over these sub-bands. This variation in molecular absorption leads to an average variation of 1 dB and 6 dBm in total attenuation (Figure 4c) and molecular noise (Figure 4d), respectively. 60 GHz was not affected much by the variation in humidity as this sub-band is mainly affected by oxygen absorption (see Figures 2b and 1).

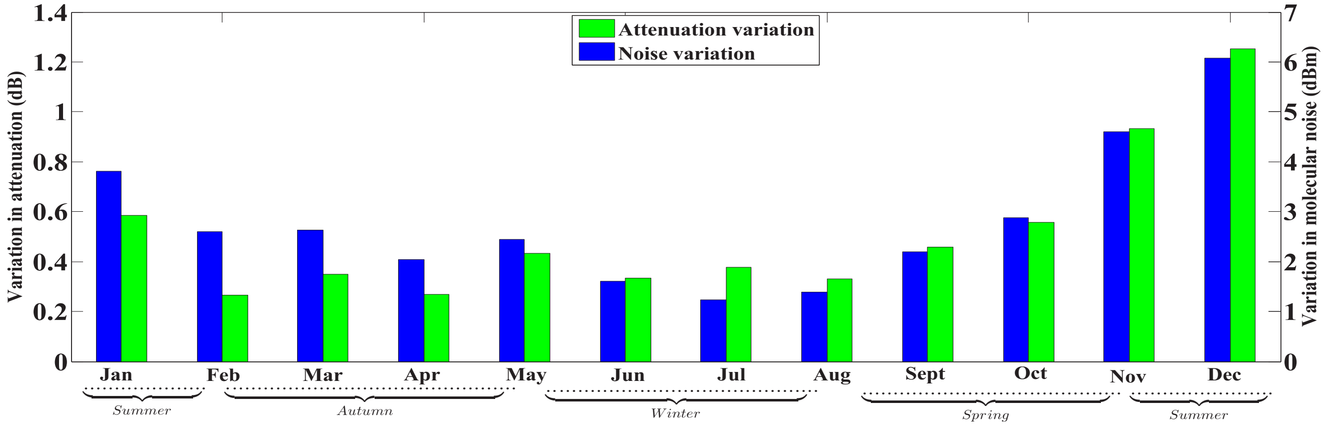


Fig. 5: Annual channel variation of 150GHz in Sydney, 2015 for an assumed distance equal to 400m.

To assess the diurnal variations over different seasons, Figure 5 plots the maximum daily variation in attenuation and noise over all 12 months in 2015, where we extract three non-rainy (clear) days for each month and average their results for that month. It is clear that the variations are noticeable in all seasons, but larger variations are expected in summer than in winter.

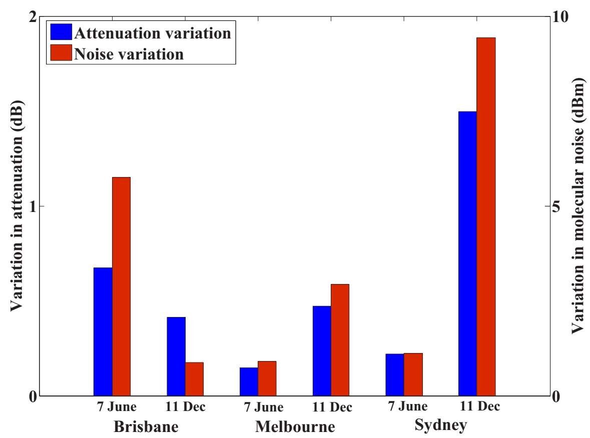
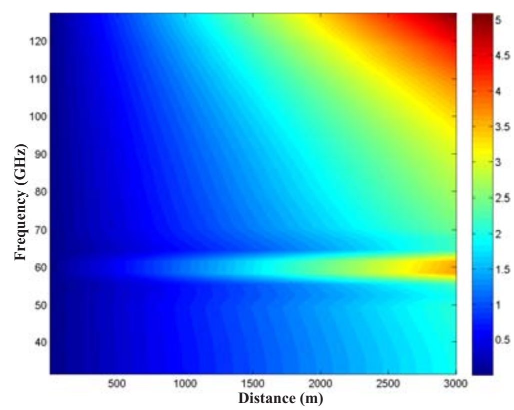


Fig. 6: Channel variation over 150GHz in different cities on 7 of June 2015 (winter) and 11 Dec 2015 (summer).

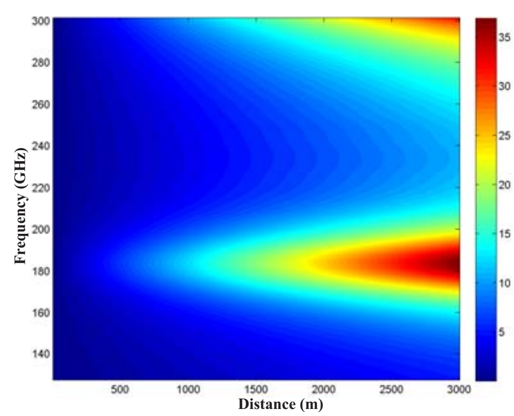
C. Other cities

Figure 6 compares the maximum diurnal fluctuation of attenuation and noise in three capital cities, Sydney, Brisbane, and Melbourne, which are all located along the east coast of the continent, but are apart by about 1000 Km each. The comparison is shown for a given day in winter (7 June 2015) and summer (11 Dec 2015) over 150 GHz sub-band. First, it shows that all three cities exhibit diurnal variation in the mmWave channel. However, while summer variation is greater than winter for both Melbourne and Sydney, it is opposite for Brisbane. Note that unlike Melbourne and Sydney, which are located in the south of the continent, Brisbane is located in the more tropical region.

D. Effect of distance



(a) Frequencies up to 130 GHz



(b) Frequencies higher than 130GHz

Fig. 7: Attenuation variation in dB as a function of distance and frequency.

So far we have studied diurnal variation for a fixed distance of 400 meter between two devices. Next, we study diurnal variation as a function of distance. This time we consider many different frequency bands within mmWave. Variations in attenuation and noise are shown as heat maps in Figures 7 and Figure 8, respectively, for Sydney (Rozelle station on 11 Dec 2015). We observe that attenuation variation is more significant at longer distances, while it is the opposite for noise variation. This is because the molecular noise is dependent on the received signal power, which fades away with the distance. Therefore at long distances, molecular noise becomes negligible. In contrast, the signal attenuation is negligible at short distances, but becomes very significant with increasing distance.

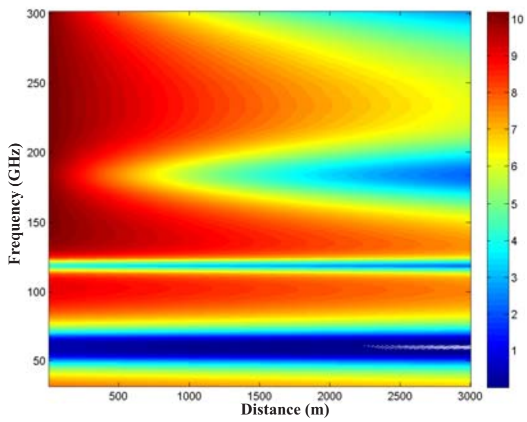


Fig. 8: Noise variation in dBm as a function of distance and frequency.

V. Conclusions and Future Works

Using hourly air quality and weather data of three cities in Australia, Sydney, Melbourne, and Brisbane, we have studied the diurnal variation of signal attenuation and noise in the mmWave spectrum. We have found that the combined effect of temperature rise and humidity fall during the day causes significant drop in attenuation and noise, which increases again during the night. This observation is consistent across all three cities studied and in all months of the year. However, the extent of variation is higher in summer compared to winter. We have also found that the 60 GHz band remains stable throughout the day as this band is mainly affected by oxygen which remains relatively stable all day around.

In this study we investigated only temporal variations of mmWave channels due to temporal variation in atmosphere. In fact, we have found that temperature and humidity also varies significantly between the coastal and interior suburbs of Sydney. In our future work we will analyze the impact of spatial variation in atmosphere on mmWave channels. Finally, we will investigate the impact of such spatio-temporal variations of mmWave channels on the higher layer protocols, systems, and services. In this paper we have considered only Line of Sight (LoS) path loss. NLOS analysis, which is much more complex and not yet fully validated in the literature, would be also an interesting future direction to follow.

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