Improving Bandwidth Efficiency in E-band Communication Systems

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INTRODUCTION

The popularity of multimedia applications and broadband Internet has created an ever increasing demand for achieving higher throughputs in cellular and wireless networks. Thus far, wireless point-to-point links have played an important role in carrying a large portion of this data by interconnecting cellular base stations or enterprise buildings. In fact, due to their low cost of installation and insusceptibility to environmental effects, more than 50 percent of today’s cellular base stations are interconnected using wireless backhaul links [1]. However, if wireless point-to-point links are expected to continue to be widely applied in next generation cellular networks, they have to support throughput comparable to that of fiber optic links. This task is made difficult by the limited bandwidth available in the microwave band [2]. In this regard, the large bandwidth available in the 70 and 80 GHz or E-band has opened up new opportunities for developing multi-gigabit-per-second wireless links [1, 3].

Even though the available bandwidth in the E-band is more than 50 times the entire cellular spectrum, radio signals in the E-band are more adversely affected by environmental factors [4]. The characteristics of E-band signals and systems can be summarized as follows:

• Due to the higher carrier frequencies, the antennas are more directional, making E-band systems mainly suitable for line-of-sight (LOS) applications.

• Rain and obstacles more severely attenuate radio signals in the E-band. Consequently, with the same transmit power and link availability requirements, E-band wireless links can operate over shorter distances compared to microwave systems. For example, let us consider two point-to-point wireless systems with a 99.999 percent availability requirement and a fade margin of 0 dB: the first system, operating at 23 GHz and employing 256-quadrature amplitude modulation (QAM), can achieve a link distance of 3 km at 1.4 Gb/s, while the second system utilizing the 70/80 GHz spectrum and using binary phase shift keying (BPSK) can only operate over 1.9 km at 3 Gb/s [4].

• To achieve the high carrier frequencies required by E-band systems, a voltage controlled oscillator’s signal needs to be taken into account for the wideband systems deployed in the E-band. Next, a new MIMO transceiver design, termed continuous aperture phased (CAP)-MIMO, is presented. Simulations show that CAP-MIMO enables E-band systems to achieve fiber-optic-like throughputs. Finally, it is argued that full-duplex relaying can be used to greatly enhance the coverage of E-band systems without sacrificing throughput, thus facilitating their application in establishing the backhaul of heterogeneous networks.

ABSTRACT

The allocation of a large amount of bandwidth by regulating bodies in the 70/80 GHz band, that is, the E-band, has opened up new potentials and challenges for providing affordable and reliable gigabit-per-second wireless point-to-point links. This article first reviews the available bandwidth and licensing regulations in the E-band. Subsequently, different propagation models (e.g., the ITU-R and Cane models) are compared against measurement results, and it is concluded that to meet specific availability requirements, E-band wireless systems may need to be designed with larger fade margins compared to microwave systems. A similar comparison is carried out between measurements and models for oscillator phase noise. It is confirmed that phase noise characteristics, which are neglected by the models used for narrowband systems, need to be taken into account for the wideband systems deployed in the E-band. Next, a new MIMO transceiver design, termed continuous aperture phased (CAP)-MIMO, is presented. Simulations show that CAP-MIMO enables E-band systems to achieve fiber-optic-like throughputs. Finally, it is argued that full-duplex relaying can be used to greatly enhance the coverage of E-band systems without sacrificing throughput, thus facilitating their application in establishing the backhaul of heterogeneous networks.
The ITU has allocated the 71–76 and 81–86 GHz bands for establishing wireless links throughout the world. Nevertheless, the channelization and regulations regarding the use of this spectrum differ in different regions and countries.

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future [7]. Thus, in this section, we examine the accuracy of the existing models for both phenomena in the E-band.

**Channel and Propagation Characteristics in E-Band**

To accurately predict the effect of environmental conditions on the performance of wireless communication systems, the ITU Radiocommunication Standards Sector (ITU-R) and Crane models have been extensively applied for link-budget planning in the microwave band. In order to determine the accuracy of these models in predicting rain intensity and the resulting signal attenuation in the E-band, a long-term measurement campaign was carried out in Gothenburg, Sweden, by Ericsson Research, where the rain intensity and signal attenuation of an E-band system were measured over a period of nine months [9]. The results of this measurement campaign and a comparison with respect to both the ITU-R and Crane models are plotted in Fig. 1. It can be observed that both the ITU-R and Crane models can rather sufficiently predict the rain intensity in this region, since the signal attenuation calculated based on the measured rain intensity is close to that of the ITU-R and Crane models. However, the measurement results in Fig. 1 show that the measured signal attenuation in the E-band is considerably higher than the attenuation predicted by both the ITU-R and Crane models. This demonstrates that both models, which are well suited for the microwave band, are not capable of accurately predicting the channel attenuation in the E-band. Thus, for E-band wireless point-to-point links to meet the expected 99.999 percent availability requirements, the fade margin needs to be chosen larger than the values calculated using the Crane and ITU-R models (e.g., 5–10 dB higher, as shown in Fig. 1). This new finding indicates that to avoid larger than necessary fade margins, more accurate channel attenuation models have to be developed for the E-band. These more accurate channel and propagation models are also anticipated to enhance the bandwidth efficiency of E-band systems.

Note that although the shortcomings of the ITU-R model in predicting the attenuation for E-band systems have also been confirmed in [8], in this work, for the first time, we present a comparison with respect to the Crane attenuation model, which is more extensively applied in North America.1

**Phase Noise Models in E-Band**

One of the main challenges in E-band communication systems is to equip the transceivers with low-phase-noise high-frequency oscillators. Nevertheless, recent studies have shown that such oscillators may be designed using Gallium-Nitride technology, waveguide theory, and optoelectronic techniques [10, 11]. Generally, two methods are proposed to generate high-frequency oscillation [10, 11]. One is to design an on-chip high-frequency oscillator, and the other is to increase the frequency of a low-frequency oscillator by means of frequency multipliers. Even though the former is expected to result in more accurate oscillators, research has shown that the design of accurate and affordable oscillators for commercial applications via this approach is a challenging task. On the other hand, the latter approach increases a low-frequency oscillator’s phase noise variance by the so-called multiplication factor [10]. As a result, oscillator phase noise is one of the main limiting factors in the application of higher-order modulations in E-band systems [4].

Although the effect of oscillator phase noise in narrowband systems has been extensively studied, there is a lack of understanding of this impairment for the wideband systems deployed in the E-band. According to traditional phase noise models, the phase noise variance or rate is linearly proportional to the sampling time applied at the receiver [5]. Therefore, it is expected that systems employing larger bandwidths and smaller sampling times will experience a smaller phase noise variance. However, by increasing the signal bandwidth, other system parameters such as the bandwidth of the receiver front-end filter must also be increased. Consequently, this leads to an increase in phase perturbation introduced to the entire communication system.

To illustrate this effect in wideband systems, Fig. 2 depicts the measured power spectral density (PSD) of oscillator phase noise for a monolithic microwave integrated circuit oscillator operating at 9.9 GHz. Figure 2 compares measurement results with the traditional Wiener phase noise model, which is extensively used in the microwave band. Note that unlike the traditional phase noise models, the phase noise PSD of an oscillator does not continue to decrease with increasing offset frequency. In fact, as

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1 The work in [8] also provides a more accurate model compared to the ITU-R model for characterizing the channel and propagation characteristics of wireless communication systems in the E-band.
The power spectral density of a free-running oscillator operating at 9.9 GHz.

Figure 2. The power spectral density of a free-running oscillator operating at 9.9 GHz.

shown in Fig. 2, in practice, the phase noise PSD exhibits a floor region beyond a certain offset frequency. Thus, as the bandwidth of a communication system increases, the floor region in the PSD of an oscillator is expected to play an important role in the overall system's performance. To verify this finding, in Fig. 3, the performance of two communication systems with different bandwidths are compared in terms of the error vector magnitude (EVM) (also known as receive constellation error) for different phase noise floor levels (signal-to-noise ratio [SNR] = 30 dB and 16-QAM). Figure 3 shows that below a certain noise floor level, the cumulative phase noise is dominant, and a system with higher symbol rate experiences a lower EVM. However, as the phase noise floor increases, the performance of a communication system employing a larger bandwidth degrades more dramatically. It is also important to consider that due to the use of frequency multipliers, it is expected that most oscillators used in E-band systems have higher phase noise floor levels. For example, if the above 9.9 GHz oscillator is used in an E-band system operating at 70 GHz, a frequency multiplier with a multiplication factor of 7 needs to be applied, which will increase the noise floor by 20log7 = 16.9 dBc. Therefore, from the results in Figs. 2 and 3, it can be concluded that the phase noise models that are used for narrowband systems (e.g., the Wiener model) cannot be applied to accurately predict the properties of this impairment in wideband systems. Thus, more accurate phase noise models for wideband communication systems have to be developed to estimate and compensate for the effect of phase noise more effectively, which in turn enables the use of more bandwidth-efficient modulation schemes.

2 This effect is not exclusive to this oscillator and is also reported in [5, references therein].

MIMO TRANSCEIVER DESIGN FOR E-BAND SYSTEMS

The development of MIMO technology has largely been based on the assumption of rich multipath, which, combined with the deployment of multiple antennas, results in multiple independent spatial channels between two terminals. Under these circumstances, it has been theoretically shown that the MIMO system capacity scales linearly with the minimum number of transmit and receive antennas. However, E-band systems are expected to operate under strong LOS conditions, thereby creating several research challenges and opportunities for the design of efficient E-band MIMO transceivers [3, 12, 13]. The antenna properties in the E-band are attractive for three important reasons:

• They result in high antenna gains for a given antenna size.
• They enable highly directional communication with narrow beams, thus reducing interference.
• They support the deployment of large-dimensional MIMO systems with relatively compact antenna arrays.

Two benchmark E-band systems dominate the current state of the art. In the first configuration, a DISH system, conventional continuous aperture “dish” antennas are used in highly directional LOS point-to-point links. Such systems are currently used for wireless backhaul links, for example, in the commercial systems offered by Siklu, E-band Communications, and Bridgewage. In the second configuration, conventional MIMO, the antenna elements are placed sufficiently far apart that the spatial LOS responses become independent. The required antenna spacing can be worked out via simple geometrical arguments and leads to the so-called Rayleigh spacing. For a given transmitter-receiver distance, the Rayleigh antenna spacing is inversely proportional to the carrier frequency. Thus, compared to microwave systems, LOS MIMO technology is more suitable for E-band systems, since the antenna spacing is smaller and the transceivers can be housed within a relatively compact module. However, while such systems can exploit multiplexing gains, they suffer from poor power efficiency and increased interference [12]. In principle, the above limitations of conventional MIMO systems can be eliminated by using half-wavelength spaced large antenna arrays. Although such systems can optimally exploit the spatial dimension, they suffer from prohibitively high transceiver complexity due to the requirement of a large number of array elements. For example, a 6° planar array operating at 80 GHz requires about 6400 antenna elements, while each antenna element requires a dedicated transceiver module [12].

Recall that propagation in the E-band is expected to have sparse multipath components and is predominantly LOS. Thus, the spatial multiplexing gain of a MIMO E-band system can, in practice, be much smaller than the minimum number of transmit and receive antennas employed. In other words, compared to a system in the microwave band, the spatial communica-
tion subspace for a MIMO E-band system can be expressed with a smaller number of orthogonal basis functions \([3, 12]\). Accordingly, to fully exploit the potential of MIMO technology and reduce the transceiver complexity, the number of beams transmitted or received by a MIMO E-band system needs to be equal to the dimensionality of the E-band channel subspace. This characteristic of E-band channels has motivated the development of the \textit{CAP-MIMO} transceiver.

\textit{CAP-MIMO} combines the multiplexing gain of MIMO systems, the antenna gain of DISH systems, and the beamforming capability of phased arrays to optimally exploit the smaller spatial dimensionality at E-band frequencies \([12]\). \textit{CAP-MIMO} uses a high-resolution discrete lens array to perform analog beamforming in the passband (Fig. 4). Essentially, in this setup, a relatively small number of active beams are radiated by the corresponding feed antennas on the focal surface of the lens array. The number of transmitted beams is directly proportional to the dimensionality of the communication channel. This approach ensures that the \textit{CAP-MIMO} transceiver is equipped with the smallest number of A/D, D/A, and radio frequency units, while fully taking advantage of the potential of MIMO technology. Figure 4 depicts the radio unit for a \textit{CAP-MIMO} system. In this setup, it is assumed that five spatially independent channels can be established between transmitter and receiver. Consequently, the \textit{CAP-MIMO} system only requires five transceiver blocks. The beam selector block in Fig. 4 ensures that appropriate beams are selected for signal transmission and reception, which is analogous to an antenna selection block in a conventional MIMO system.

Figure 5 compares the bandwidth efficiency of \textit{CAP-MIMO} with a conventional MIMO system with widely spaced antennas, and a DISH system for a point-to-point LOS link at 80 GHz. The link length is about 200 m. The antenna size for the DISH and \textit{CAP-MIMO} systems is 0.6 m \(\times\) 0.6 m with an antenna gain of 55 dBi. The conventional MIMO system has 4 widely spaced antennas at each end, where each antenna has a gain of 30 dBi. The \textit{CAP-MIMO} system is assumed to take advantage of 4 transmit and receive beams. One important observation is that the DISH system is optimum at low SNRs, whereas conventional MIMO outperforms DISH at high SNRs. \textit{CAP-MIMO} yields the best performance across the entire SNR range, thereby representing a robust scheme for realizing the advantages offered in the E-band. \textit{CAP-MIMO} can achieve a spectral efficiency of 30 b/s/Hz at a normalized SNR of \(-8\) dB with an SNR gain of about 25 dB, over the other two systems. This results in a data rate of 30–300 Gb/s for a bandwidth of 1–10 GHz. For the given antenna size, a system operating in the 3 GHz band (i.e., the microwave band, at best achieves a spectral efficiency of 10 b/s/Hz at a much higher SNR of 40 dB. This corresponds to a maximum data rate of 5 Gb/s when considering a generous bandwidth of 500 MHz. Finally, \textit{CAP-MIMO} also offers a promising route to electronic multi-beamforming and steering, which can be exploited for a number of attractive operational functions, such as user tracking in mobile environments, multi-beam steering in point-to-multipoint links, and formation of high-capacity cooperative MIMO links (discussed later in this article).

It is important to note that although the use of multi-antenna arrays in E-band systems has been studied \([6]\), they are only used for power combining and not MIMO spatial multiplexing gain. As such, the \textit{CAP-MIMO} concept presented here promises to provide spectral efficiencies that are significantly higher than the approach in \([6]\) (e.g., 30 b/s/Hz for \textit{CAP-MIMO} compared to 4.8 b/s/Hz for the approach in \([6]\)). Moreover, this article uniquely provides a comprehensive comparison between the throughput of traditional MIMO and DISH systems at different SNRs.

\subsection*{E-BAND POINT-TO-POINT SYSTEMS IN NEXT GENERATION CELLULAR NETWORKS}

With respect to point-to-point wireless links such as backhaul links, the most important issues for cellular providers are range, very high link availability, and operating costs. To facilitate the application of E-band systems in next generation cellular networks, we propose to employ full-duplex relaying to extend the range of E-band links. Moreover, the challenges and potentials for applying E-band systems for backhauling in heterogeneous networks (HetNets) are presented.

\subsection*{FULL-DUPEX MULTIHOP COOPERATIVE RELAY NETWORKS}

The research in the field of cooperative relay networks has shown that such systems can significantly enhance the coverage area and reliability of point-to-point wireless links \([14]\). Regenerative
and non-regenerative relaying, that is, decode-and-forward (DF) and amplify-and-forward (AF) relaying, respectively, have gained significant traction due to their performance and simplicity. However, most of the research in this area has focused on half-duplex cooperative relaying, where one node transmits while the remaining nodes stay silent. This approach reduces the throughput of the network for every additional hop. Moreover, although full-duplex relaying circumvents the shortcomings of half-duplex relaying, its implementation in the microwave band has been a challenging task. One approach is for the relays to transmit and receive at different frequency bands. However, such an approach is bandwidth inefficient and halves the potential system capacity for each additional hop. Another approach is to ensure that each node transmits and receives simultaneously over the same bandwidth. However, such an approach is bandwidth inefficient and halves the potential system capacity for each additional hop. Another approach is to ensure that each node transmits and receives simultaneously over the same bandwidth. However, this scheme can result in significant interference at the relay transceiver, which degrades system performance.

Recall that E-band systems employ highly directional antennas. Thus, unlike traditional microwave systems, E-band transceiver modules can operate simultaneously without significant interference. Moreover, due to the LOS nature of E-band links and higher atmospheric absorption, E-band wireless devices can be deployed in close vicinity of one another while maintaining a low level of interference (i.e., higher spatial reuse factor). These are essential features that can enable the development of full-duplex multi-relay cooperative networks in the E-band. Without sacrificing throughput, such networks can greatly enhance the range of E-band point-to-point links (Fig. 6). Moreover, AF relaying is especially attractive for full-duplex networks, since the relays may not be required to convert the signal into the baseband, thus significantly simplifying the relays’ structures and reducing their hardware costs. For example, the scenario in Fig. 6 shows that by applying appropriate beamforming schemes at the transmitter and relays, the throughput of an E-band point-to-point system can be tripled, while the link distance can be doubled.

**E-BAND SYSTEMS IN HETEROGENEOUS NETWORKS**

To meet the surge in the number of users and each user’s throughput requirements, cellular providers have resorted to increasing the number and density of macrocell base stations (BSs). However, as these throughput demands continue to grow, large BSs cannot effectively meet users’ needs in different settings (e.g., in indoor environments and at the cell edges) [15]. Moreover, macrocell BSs are expensive to deploy and maintain. Thus, next generation cellular networks are expected to adopt the HetNet paradigm, where smaller and more specialized cells are deployed by operators, such as picocells in urban areas and femtocells in indoor environments [15]. Furthermore, to mitigate interference, achieve smooth handoffs from tier to tier, and enable
cooperation among different tiers, fast backhaul links are of paramount importance.

Since picocells and femtocells have smaller coverage areas, they can be deployed more densely throughout a cellular network. Moreover, E-band systems are capable of establishing multigigabit-per-second wireless links over short distances. Thus, they are well suited for establishing backhaul links among different tiers within a cell. Due to the high atmospheric absorption and the use of highly directional antennas, they can do so without causing significant interference.

There are, however, some challenges that need to be addressed. Most femtocells are expected to be deployed in indoor environments. Since E-band radio signals do not penetrate obstacles and buildings very well, E-band backhaul links may require the application of strategically positioned relays throughout the network to establish reliable connectivity between femtocell and macrocell BSs. Another challenging issue is the high development cost of E-band transceivers. This is especially important for the development of next generation HetNets, since femtocell and picocell BSs are expected to be relatively inexpensive to manufacture. Nevertheless, recent research in the field of semiconductor design and fabrication (e.g., Silicon-Germanium and Gallium-Nitride) is expected to reduce the manufacturing costs of E-band systems and facilitate their adoption [4].

SUMMARY

In this article, to gain a better understanding of the effects of channel attenuation and phase noise on E-band systems, measurement results for both phenomena are compared against existing models. It is concluded that the ITU-R and Cane models may not be able to accurately determine the fade margin for E-band systems; for example, if these models are used to obtain the required fade margin for an E-band link with 99.999 percent availability, the result may be 5–10 dB below the actual required value. These measurements also indicate that the floor in the PSD of oscillator phase noise may more significantly influence the performance of wideband systems operating in the E-band more than it does that of narrowband systems in the microwave band. Further research in this field is anticipated to result in E-band transceivers that can employ higher-order modulations and improved bandwidth efficiency. Next, we show that the CAP-MIMO transceiver design can enable E-band systems to achieve bandwidth efficiencies of up to 30 b/s/Hz (data rates of up to 300 Gb/s). Finally, it was proposed that due to application of highly directional antennas and the LOS nature of E-band links, full-duplex relaying can be used to extend the range of E-band systems and facilitate their application in next generation heterogeneous cellular networks.

REFERENCES


A. Ghosh et al., “Heterogeneous Cellular Networks: From Theory to Practice,” IEEE Commun. Mag., vol. 50, no. 6, June 2012, pp. 54–64.

BIOGRAPHIES

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