On the Performance of Cooperative Relaying with Maximum-Ratio Combination (MRC) for mmWave Systems

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Abstract. In this paper, cooperative communication using a two-way relaying network (TWRN) is considered for millimeter-wave (mmWave) communications. Two schemes of TWRN are employed for cooperation and performance evaluation, which are amplify-and-forward (AF) and decode-and-forward (DF) relays. Furthermore, maximum-ratio combination (MRC) is utilized in each node in the proposed systems. It is noteworthy that MRC is exploited in this paper as a channel equalization and also to maximize the strength of the received signals at each node. The performance is evaluated for the proposed systems over 28 and 73 GHz using one and two parallel AF and DF relays in the presence of the direct path. Moreover, compassion between the two frequencies is achieved, via obtaining the bit-error-rate (BER) against different values of signal-to-noise ratios (SNR)’s, by assuming the same distances between the source, relay/relays, and the destination. The results show the outperforming of 28 GHz in this performance metric, i.e. BER-SNR, by using AF relaying, due to the amplification factor added to the signal to compensate for the inherent attenuation in this frequency band. Moreover, the proposed DF relay schemes have limited compensation to the attenuated signals comparing to the AF relay.

1. Introduction
It is estimated that the number of devices connected to the network has grown by a factor of 100 to 10,000 by 2021 [1]. These devices range from tablets to computers, smartphones, and PDAs, that come under the concept of the Internet of Things (IoT) [1]. Besides, by 2021, requested mobile data is estimated to have risen by a factor of 1,000 per unit. This growth puts a lot of pressure on the 4G network. This causes increases latency, signal interference, and reduction in data rates [1]. New technologies are evolving to overcome these challenges to build the next generation 5G network [1]. Large-scale MIMO (massive MIMO), full-duplex, millimeter-wave (mmWave), and cloud radio access networks (CRAN), small-cell, beamforming are some of these technologies [2]. These technologies will deliver higher network capacity, serve more customers, enhance the energy efficiency, adaptability to the implementation of new networks and devices [1]. One of the key candidate technology for wireless mobile communications within the 5th and 6th generations [3] will be millimeter-wave (mmWave) communications. With frequencies in the mmWave band ranging from 30 GHz to 300 GHz, corresponding to wavelengths of 10 mm to 1 mm [3][4][5][6]. At these rates, the uncongested spectrum of mm-Wave can easily be 200 times greater than all today’s cellular below 3 GHz [7] which will not have the ability to meet the next massive demand on services that use communication and the internet services. A mmWave communication system can support up to
multiple gigahertz of bandwidth to enhance the capacity/data rate and can be used for mobile cellular access, indoor wireless communications, or outdoor communications such as wireless mesh networks [8]. It would also play an important role in cellular networks beyond 4G and 5G[7]. The mmWaves are slightly longer than X-rays or infrared waves, but shorter than radio-waves or microwaves[6]. Moreover, mmWave's very short wavelengths allow a huge number of antenna elements to be packed into small form factors[6][7]. Such multiple antenna systems can be used for electrically steerable shaping, very high-gain manufactured arrays at the base station, in the skin of a mobile phone, or even within a chip [7][9]. Most of the latest research emphasizes the characterization of the mmWaves sub-100 GHz domain with interest in the 28 GHz band, 38 GHz band, 60 GHz band, and E-band (71 to 76 GHz and 81 to 86 GHz). These bands are planned to be employed for mobile cellular 5G [6][10] to fulfill the data rate criteria at the Gbps. Various channel models have been developed by the research community, each meeting a particular contact scenario. For example, owing to its wide unlicensed spectral resources for indoor wireless networks, most of the early modeling efforts were carried out in the 60 GHz band [4][11][12]. However, until recently, the scarcity of measurements and knowing of other mmWave bands restricted the number of channel models available. A contiguous 7 GHz frequency band from 57-64 GHz has been assigned to short-range communications on an unlicensed basis by the Federal Communications Commission (FCC) since 2001 [12]. One remarkable feature of the 60 GHz band is its availability in most parts of the world [12]. However, mmWave and current lower-frequency communications have a variety of basic variations. This includes greater loss of propagation, loss of penetration, directivity, etc. Due to these challenges, the transmission range could be reduced to a few hundred meters or less [13] to reach the guaranteed ultra-high data rates of mmWave. A promising solution for the extremely high rates of data expected in future networks for wireless systems is relay-assisted communication. Intermediate (relay) nodes may be used by relaying the signal from the source to the destination instead of a long direct link from the source to the destination, to maximize the diversity and reduce the individual transmission time [13]. In such a case, when the distance between the nodes too long to satisfy the data rate demand, the source and destination will not communicate directly with each other, and/or certain barriers between them preclude direct contact. The relays break long connections to several short links but with very high-rate that can address the high propagation loss and blockage sensitivity of mmWave [13]. Decode-and-forward (DF) and amplify-and-forward (AF) [13][14] are the most frequent relay techniques. The relays use in this work are decode-and-forward (DF) and amplify-and-forward (AF) to compensate for attenuation and corruption of signals between the transmitter and receiver in mmWave backhaul networks. While the DF relay process the received signal, the steps of processing is decoded the received data re-encodes it, and then forwards it to the destination, the received signal is only amplified and forwarded by an AF relay[13]. The complexity of DF relays is considerably higher than AF relays and decoding and re-encoding often needs maximal processing power [13]. The channel considering in this work is the mmWave channel, the feature of this channel is that the signals pass over this channel fades beyond short distance according to the high attenuation of the waves due to path losses and the obstacle absolution, plus adaptive white Gaussian noise (AWGN) is also considered. Furthermore, in our channel model, The receiver inverts the operations found in the transmitter to decode the data followed by a decoder Maximal Ratio Combining (MRC) [15] in order to improve system performance by reducing the effects of fading on system performance[16]. Maximal Ratio Combining (MRC) also known as ratio-squared combining and redetections combining. In the MRC technique signals are combined from multiple diversity branches and get multiplied by a maximal ratio combining, it is used to add signals from each channel and the gain of that channel is proportional to the signal's RMS value and inversely proportional to the mean square noise level. Each channel uses various constants of proportionality[15]. The precise problem we study is how to obtain minimum complexity of detection with the best outage probability and error probability (reduce the bit-error-rate along with different signal-to-noise ratio). The remainder of this paper is arranged as follows. Section II presented the related works. Section III, we describe the system model, Numerical and simulation results are given in section IV, while the discussion is given in section V, and concluding remarks are presented in Section VI.
1.1 Related work
The mmWave channel modeling and cooperative communication form the basis for our study. The study of mmWave channel modeling is a very hot topic, and many universities and companies are working in this field. Some of the related literature on the topic is mentioned in this scope. The characterization of the mmWaves sub-100 GHz domain with a focus on the 28 GHz, 38 GHz, 60 GHz, and E-bands (71 to 76 GHz and 81 to 86 GHz) has been the topic of most recent studies [6][10]. Various channel models have been developed by the research community, each meeting a particular contact scenario. For example, owing to its wide unlicensed spectral resources for indoor wireless networks, almost all of the early modeling attempts in the 60 GHz band were carried out [4][11][12]. However until recently, the scarcity of measurements and knowledge of other mmWave bands restricted the number of channel models available [4]. Akdeniz et al.[7] In New York, NY, USA, has been derived at 28 and 73 GHz spatial statistical channel models and channel parameters consist of angular dispersal, number of spatial clusters, outage, and loss of direction. It was discovered that powerful signals may be recognized 100-200m from possible sites for cells even in extremely NLOS environments, and it is possible to provide spatial multiplexing and variance at several Sites of multiple path clusters obtained. In New York City, an urban propagation campaign in the 28 GHz has been performed by Rappaport et al.[9], where the distance ranged from 75 m-125 m between the sender and the receiver. In Manhattan, New York, they have carried out an outage analysis [10]. In Manhattan, New York, they have carried out an outage analysis [10]. The signal received by the RX was observed to be within 200 meters for all situations, and 57 percent of positions were outages due to obstruction with most of the outages above 200 meters from the TX [17]. With a reduction of the exponent of path loss and increase antenna gains, the overall distance coverage area was seen to climb. When the TX-RX antenna gain is 49 dBi combined[17], the overall coverage distance in a heavily obstructed area exceeds 200 m. In Canada, Korea, and the United States, the 57 to 64 GHz band is available, the band from 59 to 66 GHz is available in Japan, while the band available in Australia is from 59 to 63 GHz [11].

2. System model
We consider a mmWave wireless network consisting of one source (s), one destination (D), and intermediate relays. We assume that each node of them has a sender, receiver, and antennas. The antenna technique that is used in this work is a single input single output (SISO). The intermediate relays employed in the system model are either in the AF or DF modes to support mmWave wireless backhaul and to achieve higher data rates of mmWave links. Moreover, a direct connection between sender and recipient, i.e. the line-of-sight (LoS) path, is also considered. Different scenarios are taken into account to design the network. The first scenario is to use AF relays, and the second uses DF relays in the network scheme. Besides, at each node of the network, we derive the equations.

2.1 mmWave channel assisted with AF relays
We consider the channel of mmWave from source to destination, as long as a direct path between the source and destination terminals exists, the nodes communicate via that direct path with distance $R_0$. If the direct path is blocked by a barrier or because that the signal faced high attenuation due to high carrier frequency of mmWave between the source and destination, the node indirectly communicates with each other via intermediate AF relay node (R) (in figure 1 considering one relay) we assume the source transmits the signal X, and it passes through $l_{th}$ mmWave channel. The mmWave channel can be modeled as [18]

$$h_\ell = \frac{\lambda}{4 \pi R_\ell} e^{-\frac{j2\pi R_\ell}{\lambda}}$$

(1)

Where $h_\ell$ denotes all channel paths (the amplitude of the (th mmWave channel gain) from source to destination also the path from source and destination via a relay, i.e. $h_\ell$ for ($\ell=0, 1, 2, 3, \ldots, L$). Moreover, $r_{SD}$, $r_{SR}$ and $r_{RD}$ are the distances from the source to the destination, the source and relay, and the relay and destination, respectively, where $r_{SD}$ is considered to be 200m.
at frequency $\text{=28GHz}$ as explained in [7], $r_{SR}$ and $r_{RD}$ are equal to $100m$, in which $\lambda = \frac{c}{f}$ is denoted for the wavelength with $c$ and $f$ to represent the speed of light and the operating frequency of the mmWave. The signal $x$ passes through the mmWave channel ($h_1$), the complex additive white Gaussian noise (AWGN) added to the signal at the receiver antenna of the AF relay. The direct path from source to destination, the LoS path, received signals at relay and destination are

$$y_{SD} = h_0x + n_0$$
$$y_{SR} = h_1x + n_1$$
$$y_{rd} = h_2B y_{sr} + n_2$$

In the AF relaying scheme, the received signal in the relay is amplified by a gain factor $B$ and then forwarded to the destination, where $B$ is defined as the amplification factor scaling of the relay transmitted power. This indicates that the transmitted average power is constant at the relay ($p_r$) [13]. Therefore, $B$ can be derived as

$$B \leq \sqrt{\frac{p_r}{h_1^2E[|x|^2]+E[|n_1|^2]}}$$

where $p_r$ is the signal power, and $E[.]$ represents the expectation of signal and noise. The received signals from each channel are added together at the received node, which can be written as equation (6), then decoded by MRC decoder to overcome the channel effects on the signal, by made the gain of each channel proportional to the root-mean-squared (r.m.s) value of the signal and made the gain in that channel inversely proportional to the mean square of the noise level [15]. Furthermore, the original shape of the signal can be restored by using this technique. The reconstructed signal at the receiver can be written as in equation (6), in which equalization by using the MRC technique is utilized to maximize the signal strength by combining all paths at the destination.

$$\hat{x} = h_0^* y_{sd} + h_1^* B^* h_2^* y_{rd}$$

The second scenario in this section is shown in figure 2, in which two AF relays in a parallel transmission model for the sake of improving the performance of the system by maximizing outage probability, minimizing the error probability, and enhancing the diversity gain. In this scenario the transmitted signal ($x$) is propagated through three paths to reaches the destination, the first is the direct path as illustrated in equation (2). The two other paths are indirect paths with intermediate AF relays between the source and destination to make them communicates with each other. The use of two relays in the system model instead of one relay is to achieve the lowest bit-error-rate (BER) at the destination. The received signals at the destination node from the relays $R_1$ and $R_2$ can be expressed as:
\[ y_{sr1} = h_1 x + n_1 \]  
\[ y_{r1d} = h_2 B_1 y_{sr1} + n_2 \]  
\[ y_{sr2} = h_3 x + n_3 \]  
\[ y_{r2d} = h_4 B_2 y_{sr2} + n_4 \]

\[ n_1 \leq \sqrt{\frac{P_r}{h_1^2 E[|x|^2] + E[|n_3|^2]} \]  
\[ \hat{x} = h_0^* y_{sd} + h_1^* h_2^* B_1^* y_{r1d} + h_3^* h_4^* B_2^* y_{r2d} \]

2.2 mmWave channel assisted with DF relays

In the network model that is shown in figure 3, we consider DF relay instead of AF relay that presented in the network model in figure 1. In DF relaying sketch, the received signal by the relay ( \( y_{sr} \)) is processed and then send to the destination. The processing operation is achieved by decoding, re-encoding, and retransmitting it to the next node.

In the direct path, the received signal at the destination, \( y_{sd} \), can be written as:
\[ y_{sd} = h_0 x_1 + n_0, \]
while the received signal at the relay, \( y_{sr} \), is expressed as:

\[
y_{sr} = h_1 x_1 + n_1, \tag{14}
\]

where the DF relay performs equalization as in equation (15) to obtain the estimated symbol \( \hat{x}_1 \), which is decoded, re-encoded, and transmitted to the destination.

\[
\hat{x}_1 = h_1^* y_{sr} \tag{15}
\]

The transmitted symbol, which is denoted as \( x_2 = \hat{x}_1 \), is passed through a mmWave channel \( h_2 \) towards the destination. The DF relay utilizes the MRC equalizer to remove the channel effects on the signal, so the original signal \( \hat{x}_1 \) is restored, decoded, and re-transmit again to reach the destination node as

\[
y_{rd} = h_2 x_2 + n_2 \tag{16}
\]

In this type of relay, AWGN is not accumulated due to the decoding process at the relay [19]. This feature is not found in AF relay so it helps to improve the achievement of the network. The reconstructed signal is given by

\[
\hat{x}_1 = h_0^* y_{sd} + h_2^* y_{rd} \tag{17}
\]

\[\text{Figure 4. mmWave channel assisted with two DF relays.}\]

The second scenario of DF relay is similar to that described in Figure 2, in which the signals received by two parallel relays R1, R2. The received signals at the two relays are expressed as

\[
y_{sr1} = h_1 x_1 + n_1, \tag{18}
\]

\[
y_{sr2} = h_3 x_1 + n_3. \tag{19}
\]

The signals that reach the destination node from the relays and the source are expressed as

\[
y_{sd} = h_0 x_1 + n_0, \tag{20}
\]

\[
y_{r1d} = h_2 x_2 + n_2, \tag{21}
\]

\[
y_{r2d} = h_4 x_3 + n_4, \tag{22}
\]

While the reconstructed signal is written as

\[
\hat{x}_1 = h_0^* y_{sd} + h_2^* y_{r1d} + h_4^* y_{r2d} \tag{23}
\]
3. Simulation Results

We simulate the proposed systems shown in figures (1-4) using Monte-Carlo simulations via Matlab programming. AF and DF relays are considered to assist the communication between a source and destination over 28 and 73 GHz mmwaves, in which binary phase-shift keying (BPSK) is employed as a modulation scheme in the proposed systems. Two scenarios are considered for the AF and DF relaying by utilizing one and two relays in parallel between the transmitter and receiver in the presence of the direct link between them. The distance between the source and destination is assumed 200m and the one or two relays is/are placed in the middle between them. Figure 5 shows the first scenario for the two frequencies mentioned above, in which one relay is used, as in Figure1 and Figure3 for the AF and DF relaying, respectively. This figure demonstrates two outcomes, the first that 28GHz has better BER-SNR performance than 73GHz, while the second shows the outperform of AF relay over DF relay for compensation of the inherent attenuation that existed in these frequency bands.

![Figure 5 BER vs. SNR for cooperative relaying for mmWaves using one AF and DF relays over 28 and 73 GHz in the presence of the direct path.](image-url)

Figure 6 shows the BER-SNR performance for the systems shown in figure 2 and figure 4, in which two parallel AF and DF relays are used in the presence of the LOS link, and for the same distances mentioned above. It is noteworthy, that all channels are created in this paper randomly, and no correlation between them.
Figure 6 BER vs. SNR for cooperative relaying for mmWaves using one and two parallel AF and DF relays over 28 GHz in the presence of the direct path.

4. Conclusions:
Cooperative communications via relays have been considered in this paper to compensate for the inherent attenuation of the signal passed through mmWave channels. AF and DF relaying schemes have been employed, along with utilizing maximum-ratio combination (MRC) in each node in the proposed systems. The MRC technique has been exploited to equalize the mmWave channels and to maximize the strength of the received signals at each node. The performance has been evaluated, using one and two parallel AF and DF relays for the proposed systems, over 28 and 73 GHz in the presence of the LoS link. Moreover, compassion between the two frequencies has been achieved, via obtaining the BER-SNR performance, considering the same distances between the nodes for all scenarios. The results revealed 28 GHz has better BER-SNR by using AF relay, due to the amplification factor added to the signal to compensate for the inherent attenuation in this frequency band. Moreover, the two DF relay schemes did not add valuable compensation to the signals comparing to the AF relay.

5. References
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