Research Article
Buffer-Aided Cooperative Millimeter Waves for IOT Networks

Mohammad Alkhawatrah [iD]

Department of Electronics and Communications Engineering, Al-Ahliyya Amman University, Amman, Jordan

Correspondence should be addressed to Mohammad Alkhawatrah; m.alkhawatrah@ammanu.edu.jo

Millimeter-wave (mm-Wave) communications is a promising technology for the next wireless generations and applications such as IoT networks because of its massive bandwidth which increases the system capacity. However, mm-wave is susceptible to huge path loss and obstacle blocking, and this is largely narrowing the coverage of the mm-wave signals. Therefore, several techniques are used to enhance mm-wave performance such as multiple-input multiple-output (MIMO) and cooperative solutions such as relays. For instance, traditional relaying techniques (without buffers) are utilized to mitigate mm-wave path loss and blocking, as it provides an alternative path that could have lower path loss and it could help in avoiding obstacles. Nonetheless, traditional relaying techniques are outperformed by buffer-aided relaying techniques which achieve higher throughput and lower outage in the microwave frequencies. In this paper, we propose utilizing buffer-aided relays with a finite buffer-size instead of conventional relays in mm-wave networks motivated by the positive impact of the buffer-aided relay in lower frequency bands (microwave band). In the simulations, all sources, relays, blockages, and users are distributed in the network as a Poisson point process with various densities. Simulation experiments show that the proposed relay-assisted mm-wave network with buffering capabilities outperforms the conventional relay in both throughput and coverage and achieves about 3 dB gain. This superiority of the proposed solution holds in different scenarios such as increasing the ratio of the blockages or decreasing the ratio of relays. In particular, employing buffer-aided relays has almost the same effect of doubling the number of conventional relays, which is cost and spatial effective. Furthermore, in the majority of buffer-aided relays studies, the impractical infinite buffer-size is considered; however, the proposed solution utilizes a practical finite buffer-size with prioritizing transmission, and the results show that the practical solution can outperform the infinite buffer-size solution in the mm-wave networks.

1. Introduction

Recent advancement in wireless communications has encouraged the rapid growth of the Internet of Things (IoT) with its ultracomputing capabilities to interconnect a massive number of different objects to the Internet. IoT is the development of the Internet services so as to integrate each and every object which exists or is going to exist in the future, such as radio frequency identifications, sensors, and actuators. These applications require to massively connect new devices and to exchange tremendous amount of data. For instance, the capacity demand in the next decade is expected to witness a 1000-fold increase. This hugely increasing demand for data traffic and massive connectivity could be realized by new signal processing techniques, densifying the network, or exploiting additional frequency bands [1, 2]. Millimeter-wave (mm-wave) exploits new bands (30 to 300 GHz), where the huge unused bandwidth in these bands allows the wireless systems to support the enormous increase in capacity demand since capacity of wireless systems increases when the exploited bandwidth increases, which makes mm-wave an attractive candidate for realizing the current as well as the future IoT compared with the currently crowded microwave band (0.3 to 3 GHz) [3].

Mm-wave communication has gathered considerable attention from researchers for its capabilities to support the exponentially increasing demand for massive bandwidths. To this end, 3GPP has considered the feasibility of mm-wave frequencies for wireless communication [4, 5]. However, because of the flimsy diffracted mm-wave signal and the

severe penetration loss of mm-wave, communication at mm-wave is extremely weak against blockages. For instance, measurements of mm-wave propagation at 28 GHz through brick pillars have a penetration loss of 28.3 dB, which is about 20 dB worse than microwave frequency signals. Even in indoor environments, human bodies are mm-wave blockages [6, 7]. In other words, mm-wave blockages are everywhere, and to avoid the massive penetration loss, the transmissions in mm-wave networks are extensively limited to line-of-sight (LOS) paths, which reduces coverage tremendously [8].

The severe attenuations make mm-wave quite challenging when applied to the IoT [9]. Several solutions are proposed in the literature, such as designing a special antenna to make mm-wave suitable for IoT [10]. Another type of solution is based on combining mm-wave with promising technologies such as massive multiple-input multiple-output (MIMO) which can produce high-precoding gains to compensate for the attenuations of mm-wave [11]. However, the complexity of MIMO can be avoided with relaying solutions [12].

A valid solution to extend coverage in mm-wave networks is employing an intermediate relay node to help the transmission from a source to a destination that has a poor direct link to the source. The improvement that using relays provides is due to the relay's ability to provide another path from the source to the destinations around obstacles. Generally, a relay node can either be a dedicated relay or can be performed in the form of user cooperation where a middle idle user acts as a relay. Relay nodes have been used in modern communications and form a part of LTE release 10 because of their ability to enhance the system coverage and capacity in networks of microwave frequencies [13, 14]. Therefore, several studies suggest employing relays in 5G mm-wave networks to mitigate the coverage dilemma.

As stated in [15], applying the results of microwave band frequencies to mm-wave is nontrivial due to their differences in propagation properties and the signal high directivity. Accordingly, several studies have been undertaken to evaluate the benefits of using a relay in mm-wave communications [16]. In [17], the authors study cooperative communications for frequencies above 10 GHz and examine the coverage probability using relay transmission. The results show that using relays improves the coverage probability. In [18], multihop relaying is proposed to improve the coverage probability of mm-wave networks. Nonetheless, the large number of hops increases signaling overhead, delay, and interference.

In [19], the authors use stochastic geometry to study the improvements in coverage probability for a relay-assisted mm-wave network. The results validate the benefits of selecting the best relay, the relay with the highest end-to-end signal-to-noise ratio (SNR), on coverage probability in mm-wave networks. Furthermore, buffer-aided relays have enhancements in coverage probability and throughput compared with conventional relays. This is due to the flexibility that buffers provide, so transmitting and receiving do not have to be successive. Inspired by the benefits of buffer-aided relays on microwave frequency, the authors in [20] have employed full-duplex relays which are equipped with infinite size buffer. The authors focused on the trade-off between system throughput and delay, and in addition, the authors attempted to ease the difficulties of stability in infinite buffer-size (unlimited queue). However, as shown in [21], using an infinite size buffer is impractical due to its ability to lengthen the delay to an unacceptable limit.

To the best of the authors' knowledge, none of the available studies has considered a buffer-aided relay with a finite buffer-size in mm-wave networks. Motivated by this and by the fact that considering the buffer state in the relay selection has benefits on reducing outage probability in microwave frequencies (see [22–26]), this paper considers a finite buffer-size for the buffer-aided relay in mm-wave networks. In summary, the main novelty of this paper is to utilize relays with finite buffer-size in relay-assisted mm-wave networks to make it sufficient for IoT. Furthermore, the relay selection rule is not only based on the link state (this is the case with the available relay-assisted mm-wave studies), but the buffer state is also considered in the selection to avoid full and empty buffers. As a result, using a buffer-aided relay with a finite buffer-size improves the throughput and the coverage of the mm-wave. This adds to the value of utilizing mm-wave in realizing IoT and makes mm-wave more capable to meet the IoT requirements for higher data-rate and massive connectivity.

The main contributions in this paper are listed as follows: (1) we study the performance enhancements of the buffer-aided relay in relay-assisted mm-wave networks rather than using traditional relays. (2) The throughputs and the coverage of the proposed system are tested in different blockage and relay density scenarios and compared with other available solutions. (3) The simulation experiments via PPP validate the superiority of the proposed system compared with the available solutions. (4) We study the impact of utilizing a practical buffer size instead of an infinite buffer.

The organization of this article is as follows: Section 2 includes the system model for the buffer-aided relay solution in mm-wave networks. Performance analysis is presented in Section 3. Numerical simulation experiments of the proposed system in addition to comparison with other available systems are thoroughly discussed in Section 4. Finally, Section 5 concludes the paper.

2. System Model

Stochastic geometry evolves a tractable model to evaluate the performance of wireless networks. The Poisson point process (PPP) is the most popular point process to model the locations of sources and users in wireless networks which can be utilized to determine the outage probability [27]. Therefore, we consider a stochastic geometry approach (PPP) to characterize the locations of the relays, the obstacles, and sources which all are assumed to be independent of each other. The number of relays in the network is not fixed to make our proposed study more realistic and suitable for practical outdoor environments which have a dynamically varying network topology. The system model of the proposed relay-assisted mm-wave with buffering capabilities
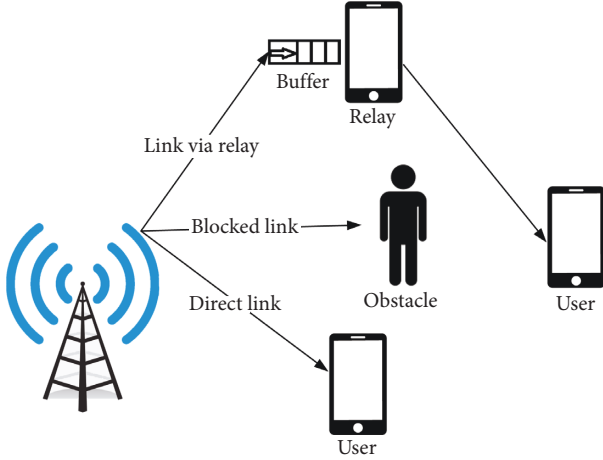
Figure 1: Relay-assisted mm-wave network with buffering capabilities in the system model.

is shown in Figure 1. Figure 1 shows two users: one user has a direct link with the source (e.g., base station), and the other user does not have a direct link with the source because the obstacle blocks this link. Hence, a buffer-aided relay provides an alternative link between the source and the blocked user.

2.1. Relay Networks. The relays in the proposed system are half-duplex (HF) decode-and-forward (DF) and denoted as R, and sources and users are denoted as S and U, respectively. Each relay R is equipped with one L-size buffer for data storing. The channel coefficients for the $S - R$, $S - U$, and $R - U$ links are denoted as h_{sr}, h_{su}, and h_{ru}, respectively. All channels have a flat Rayleigh fading coefficient that remains constant within each time slot and changes independently from one time-slot to another. Without losing generality, we assume the transmit power P_t at all transmitting nodes and the assumption for the noise variances at all receiving nodes to be σ^2. The data rate is assumed to be fixed at a value of ϵ. If the link capacity is greater than or equal to ϵ, the link is up, and the transmission is successful. The channel state information at the receivers is assumed to be available. At a time-slot t, the corresponding link capacities for channels h_{sr}, h_{su}, and h_{ru} are given by

$$C_{sr}(t) = \log_2\left(1 + \gamma_{sr}(t),\right.$$

$$C_{su}(t)) = \log_2\left(1 + \gamma_{su}(t)\right),$$

$$C_{ru}(t) = \log_2\left(1 + \gamma_{ru}(t)\right), \tag{1}$$

where $\gamma_{sr}(t) = (P_t/\sigma^2)|h_{sr}(t)|^2$, $\gamma_{su}(t) = (P_t/\sigma^2)|h_{su}(t)|^2$ and $\gamma_{ru}(t) = ((P_t/\sigma^2)|h_{ru}(t)|^2)$. The channel gains $|h_{sr}(t)|^2$, $|h_{su}(t)|^2$, and $|h_{su}(t)|^2$ are exponentially distributed with the average $\theta_{sr} = E[|h_{sr}(t)|^2]$, $\theta_{su} = E[|h_{su}(t)|^2]$, and $\theta_{ru} = E[|h_{ru}(t)|^2]$, where $E[.]$ is the expectation. $\gamma_{sr}(t)$, $\gamma_{su}(t)$ and $\gamma_{ru}(t)$ are also exponentially distributed with average $\overline{\gamma}_{sr} = (P_t/\sigma^2)\theta_{sr}$, $\overline{\gamma}_{su} = (P_t/\sigma^2)\theta_{su}$ and $\overline{\gamma}_{ru} = (P_t/\sigma^2)\theta_{r_u}$. Thus, $\gamma_{sr}(t)$, $\gamma_{su}(t)$, and $\gamma_{ru}(t)$ are the instantaneous SNR, while $\overline{\gamma}_{sr}$, $\overline{\gamma}_{su}$, and $\overline{\gamma}_{ru}$ are the average

SNR for channels $h_{sr}(t)$, $h_{su}(t)$, and $h_{ru}(t)$, respectively. An outage occurs if the link capacity is less than the target data rate, and the outage can be calculated utilizing the fact that $\gamma_{sr}(t)$, $\gamma_{su}(t)$, and $\gamma_{ru}(t)$ are exponentially distributed with CDFs as follows:

$$P\{\log_2\left(1 + \gamma_{sr}(t)\right) < \varepsilon\} = 1 - e^{\left(-2^\varepsilon - 1/\overline{\gamma}_{sr}\right)},$$

$$P\{\log_2\left(1 + \gamma_{su}(t)\right) < \varepsilon\} = 1 - e^{\left(-2^\varepsilon - 1/\overline{\gamma}_{su}\right)}, \tag{2}$$

$$P\{\log_2\left(1 + \gamma_{ru}(t)\right) < \varepsilon\} = 1 - e^{\left(-2^\varepsilon - 1/\overline{\gamma}_{ru}\right)}.$$

2.2. Relay-Assisted mm-Wave. The locations of sources, blockages, and users are all modeled as Poisson point processes with densities λ_s, λ_r, and λ_u, respectively. The users are assumed to be allied to the nearest sources. An LOS link is the no blockage link between S and U. While a non-line-of-sight (NLOS) link is the link with a blockage between S and U. In general, the probability of LOS increases with shorter distances, while the probability of NLOS increases with longer distances. Relays can be employed in the mm-Wave network to enhance the overall performance. U that experiences NLOS link can be linked to the nearby R for a lower path loss. Relays are also distributed as PPP with a density λ_r. By using relays, the average distance between U and nearest R is shorter than the average distance between U and nearest S. Therefore, more LOS links are anticipated with the help of R. Hence, the average path loss between U and R is expected to be lower than the average path loss between U and S. We follow the similar calculations in [28–31].

2.3. Joining Rule. U is linked to the nearest S or R. The probability density function (PDF) of the distance d between U and its nearest S or R can be calculated as [28]

$$f_{d\,i\longrightarrow u}(d) = 2\pi\lambda_i d e^{-\lambda_i \pi d^2}, \quad i \in \{s, r\}, \tag{3}$$

where $f_{d\,s\longrightarrow u}(d)$ and $f_{d\,r\longrightarrow u}(d)$ represent the PDF of the $S - U$ link and $R - U$ link, respectively. When U experiences NLOS link to its nearest BS, it switches to the nearest R to establish a two-hop connection to the nearest S.

2.4. Blockage Model. After getting the distance d between the U and S or R from (3), the probability that the link has LOS is given as [29]

$$P(LOS|d) = e^{\left(-2\,d\lambda_b\,(E[H]+E[W])/\overline{\pi}\right)}, \tag{4}$$

$E[H]$ and $E[W]$ are the average height and width of blockages, respectively. These two parameters describe the size of blockages. Hence, NLOS probability is simply $P(\text{NLOS}|d) = 1 - P(\text{LOS}|d)$.

2.5. Path Loss Model. The path loss in dB for an LOS link of distance d is modeled as [30]:

$$PL_{\text{LOS}}(d)_{dB} = 20\log_{10}\frac{4\pi}{\lambda} + 10\alpha_L\log_{10}d + \chi_{\sigma_L}, \qquad (5)$$

α_L is the path loss exponent of an LOS link, and $\chi_{\sigma L}$ is the LOS case shadowing, which is a normal distribution in dB (lognormal distribution in linear scale) with zero mean (dB) and standard deviation σ_L (dB). For an LOS link, σ_L is usually small and has a small effect on path loss. The path loss in dB for an NLOS link with distance d is similar to the path loss for an LOS link with a different path loss exponent and shadowing standard deviation. It can be written as [30]

$$PL_{\text{NLOS}}(d)_{dB} = 20\log_{10}\frac{4\pi}{\lambda} + 10\alpha_N\log_{10}d + \chi_{\sigma_N}. \qquad (6)$$

where α_N is the path loss exponent for an NLOS link, and σ_N is the standard deviation of shadowing for an NLOS link. σ_N is usually huge and has a massive effect on the path loss. In mm-wave networks, interference is relatively small compared with noise and the system works in a noise-limited mode [30]. Therefore, interference is ignored, and SNR in the LOS case is (see [31])

$$\text{SNR}_{\text{LOS},i\longrightarrow u} = \frac{P_t G_i G_u h_{iu} PL_{\text{LOS}}^{-1}}{N}, \quad i \in \{s,r\}, \qquad (7)$$

where G_s, G_r, and G_u denote the antenna gain for S, R, and U antennas, respectively, PL_{LOS}^{-1} is the inverse of LOS path loss in (5), but in the linear scale, $N = BW \times \sigma^2$ is the noise power and BW is the bandwidth. Similarly, the SNR for NLOS case is (see [31])

$$\text{SNR}_{\text{NLOS},i\longrightarrow u} = \frac{P_t G_i G_u h_{iu} PL_{\text{NLOS}}^{-1}}{N}, \quad i \in \{s,r\}, \qquad (8)$$

where PL_{NLOS}^{-1} is the inverse of NLOS path loss in (6) but in the linear scale.

3. Performance Analysis

The capability of the buffer-aided relays reduces the outage probability, and hence, the system throughput is improved. This makes the buffer-aided relay an attractive solution to exploit the wide BW of the mm-wave efficiently. This section validates analytically the superiority of the buffer-aided relay compared with the conventional relay. We start with analyzing the buffer-aided relay. In each buffer-aided relay, the number of the stored data packets serves as a state. Assuming that there are M relays with L buffer size, there are $(L+1)^M$ states. Every state affects the numbers of the available $S - R_m$ and $R_m - U$ links. Any $S - R_m$ link is available when the receiving buffer is not full, and any $R_m - U$ link is available when the transmitting buffer is not empty. Noting that since S-U link is common in the buffer-aided and the conventional relay systems, it can be ignored safely during the comparison. The l-th state vector is defined as

$$\mathbf{s}^{(l)} = \left(s_1^{(l)}, s_2^{(l)}, \ldots, s_M^{(l)}\right), \quad l = 1, \ldots, (L+1)^M, \qquad (9)$$

where $s_m^{(l)}$ is the buffer length at R_m at state $\mathbf{s}^{(l)}$.

By taking all states in account, the outage probability is the probability that the system remains at the same state, which means that no communication happened (transmitting or receiving) during the current time slot. Thus, the outage probability of the buffer-aided system can be obtained as

$$P_{\text{out}} = \sum_{i=1}^{(L+1)^M} P_{\text{out}}^{\mathbf{s}^{(i)}}\pi_i, \qquad (10)$$

where π_i is the stationary probability for the state $\mathbf{s}^{(i)}$, and $P_{\text{out}}^{\mathbf{s}^{(i)}}$ is the outage probability at the state $\mathbf{s}^{(i)}$. Assuming that all links are independent and identically distributed (i.i.d), the outage occurs if all $S - R_k$ and all $R_k - U$ links are in outage:

$$P_{\text{out}} = \left(1 - e^{-2^{\varepsilon}-1/\overline{\gamma}_{SR_m}}\right)^{O_{\mathbf{s}^{(l)}}^{SR_m}} \times \left(1 - e^{-2^{\varepsilon}-1/\overline{\gamma}_{R_mU}}\right)^{O_{\mathbf{s}^{(l)}}^{R_mU}}, \qquad (11)$$

where $O_{\mathbf{s}^{(l)}}^{SR_m}$ denotes the number of available $S - R_m$ links at state $\mathbf{s}^{(l)}$, and $O_{\mathbf{s}^{(l)}}^{R_mU}$ is the number of available $R_m - U$ links at state $\mathbf{s}^{(l)}$.

In buffer-aided relays, buffer states are modeled as a discrete time Markov chain with transition matrix $\mathbf{A}$ representing $(L+1)^M \times (L+1)^M$ state transition. $\mathbf{A}_{ij}$ is the notation for the i th row and j th column entry, which expresses the transition probability to move from state $s^{(j)}$ at time t to state $s^{(i)}$ at time $t+1$:

$$A_{ij} = P\left(X_{t+1} = s^{(i)}|X_t = s^{(j)}\right). \qquad (12)$$

The described Markov chain is irreducible and aperiodic. The Markov chain is irreducible if every state is reachable by all other states, and if the probability of staying at any state is higher than zero, the Markov chain is aperiodic, see [32, 33]. As presented in [22], in irreducible and aperiodic Markov chain, the stationary state probability vector is obtained as

$$\boldsymbol{\pi} = (\mathbf{A} - \mathbf{I} + \mathbf{B})^{-1}\mathbf{b}, \qquad (13)$$

where $\boldsymbol{\pi} = [\pi_1, \pi_2, \ldots, \pi_{(L+1)}]$, π_i is the probability that state is $\mathbf{s}_i$, $\mathbf{b} = [1, \ldots, 1]^T$, $\mathbf{I}$ is the notation of the identity matrix, and $\mathbf{B}$ denotes an $(L+1) \times (L+1)$ ones matrix. Now, we can calculate the outage probability of the buffer-aided relay system when the Markov chain remains in the same state as follows:

$$P_{\text{out}} = \sum_{i=1}^{(L+1)^M} \pi_i \mathbf{A}_{ii}, \qquad (14)$$

where $\mathbf{A}_{ii}$ are the diagonal elements of $\mathbf{A}$.

Unlike the case with the traditional relay where both $S - R$ and $R - U$ links have to be up to success in transmission, in the buffer-aided relay, any available $S - R$ or $R - U$ is enough for successful communications. Hence, the diversity gain of the buffer-aided relay system is twice that for the traditional relay system (see [34]). Therefore, the outage probability is reduced when buffer-aided relays are used instead of the traditional relays:

$$1 - \left(\left(e^{\left(-2^{\varepsilon}-1/\overline{\gamma}_{sr}\right)}e^{\left(-2^{\varepsilon}-1/\overline{\gamma}_{ru}\right)}\right)\right) \geq 1 - \left(e^{\left(-2^{\varepsilon}-1/\overline{\gamma}_{sr}\right)} + e^{\left(-2^{\varepsilon}-1/\overline{\gamma}_{ru}\right)}\right). \qquad (15)$$

TABLE 1: Simulation parameter values.

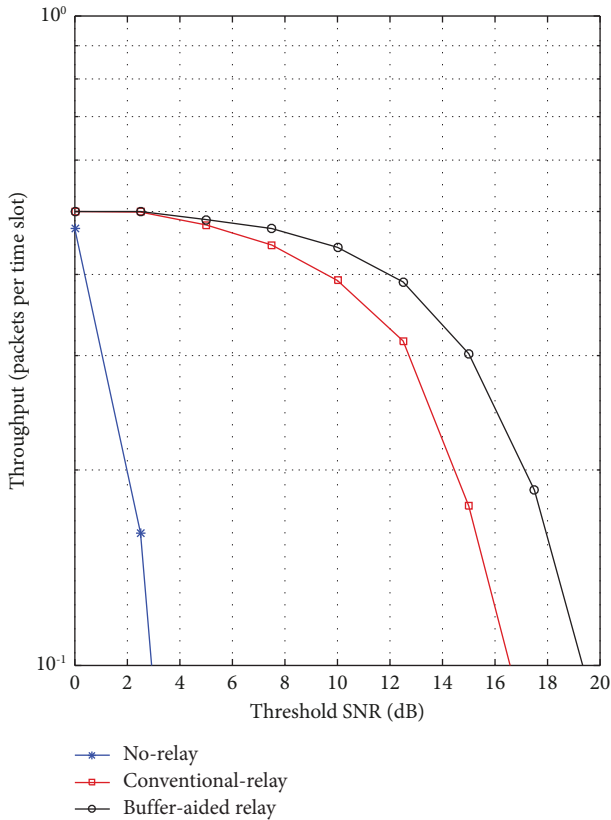| Parameter	Value
Transmitted power P_t	27 dBm
Source antenna gain G_s	3 dBi
Relay antenna gain G_r	30 dBi
User antenna gains G_u	5 dBi
LOS path-loss exponent α_L	2.1
NLOS path-loss exponent α_N	3.4
LOS standard deviation σ_L	3.6 dB
NLOS standard deviation σ_N	9.7 dB
Sources density λ_s	$3.1831 \times 10^{(-5)}$
Blockages density λ_s	$100 \times \lambda_s$
Bandwidth BW	1 GHz
Relays density λ_r	$10 \times \lambda_s$
Users density λ_u	$200 \times \lambda_s$
Expected height $E[H]$ and width $E[W]$	2 m
Noise power N	$3.89 \times 10^{(-9)}$ w
Buffer-size L	5

FIGURE 2: Outage probability comparison between the available solutions and the proposed solution.

knowing that $0 \leq e^{-2^{\epsilon}-1/\overline{\gamma}} \leq 1$ (probability). For the delay-limited transmission as in [35, 36], the average throughput $\overline{\xi}$ is obtained as

$$\overline{\xi} = \epsilon(1 - P_{\text{out}}), \tag{16}$$

which clearly shows that the buffer-aided relay system outperforms the traditional one in the system throughput since it has lower outage probability.
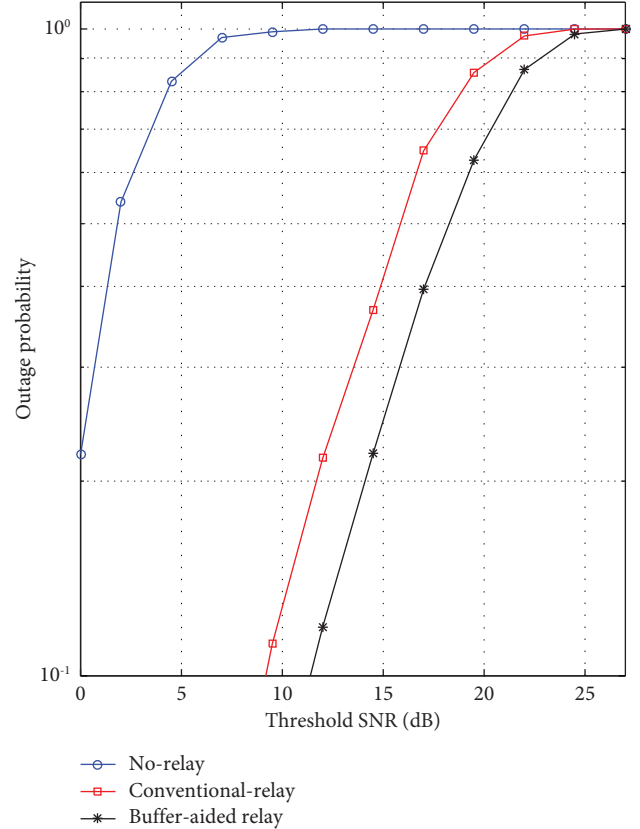

FIGURE 3: Throughput comparison between the available solutions and the proposed solution.

4. Simulation Experiments Results

This section presents the simulation experiment results in order to validate the proposed relay-assisted mm-wave with buffering capabilities. In addition, this section provides performance comparisons between the proposed system and the available related solutions in [30, 31]. All sources and relays are assumed to operate at 28 GHz. In the simulations, to study the performance of the proposed system, we set the values of the described parameters in the system model similar to the values in [30, 31]. The parameters are listed in Table 1, and any altering of these values will be stated.

Figure 2 shows a throughput comparison between the available solutions and the proposed solution. Specifically, the mm-wave network with no-relay [30], the traditional relay-assisted mm-wave [31], and the proposed relay-assisted mm-wave with buffering capabilities are all compared in Figure 2. The superiority of the relay-assisted mm-wave solutions over no-relay solution is obvious, and the proposed system (with buffer) boosts the improvement in the performance of the relay-assisted mm-wave. For instance, the throughput that the traditional relay-assisted achieves at the threshold SNR = 13 dB is about 0.3 packets per time-slot, a similar throughput is achieved in the proposed solution at a higher threshold SNR = 15 dB (knowing that increasing the SNR threshold restricts the reception to higher signal strength). This means that the gain of the proposed system is about 3 dB. It is worth mentioning that at
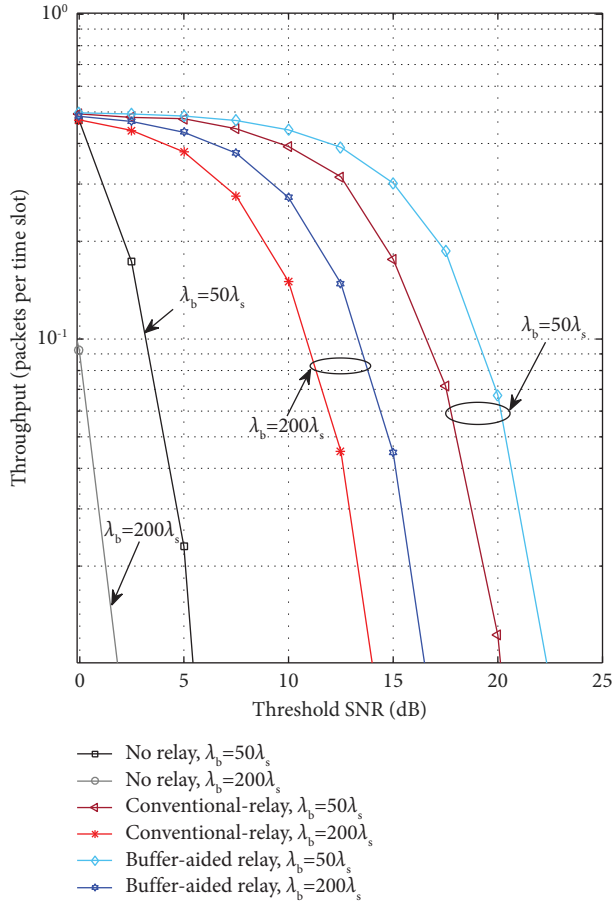
FIGURE 4: The impact of different blockage densities on the available solutions and the proposed solution.

FIGURE 5: The impact of different relay densities on the relay-assisted mm-wave and the proposed solution.

very low SNR thresholds (less than 0 dB), the direct link (no-relay case) achieves higher throughput than relay-assisted cases because the relay transmission occurs in two hops instead of one hop (half-duplex). Therefore, employing relays is necessary for more realistic higher threshold systems. This can be seen in Figure 3, where the no-relay mm-wave transmission is completely blocked at the threshold SNR = 10 dB, while in the relay-assisted cases, the transmission is completely blocked at 24 dB (for the traditional) and 27 dB (for the proposed).

In Figure 4, the impact of different densities of blockage is thoroughly studied. In particular, different blockage densities are simulated for the three solutions: no-relay, conventional-relay, and the proposed buffer-aided relay. It is obvious that as the density of blockages increases, the no-relay case goes out of the comparison. For example, if $\lambda_b \geq 50 \times \lambda_s$, a throughput of 0.3 packets per second is unreachable even for low SNR thresholds such as 2 dB. Although utilizing traditional-relays has a massive improvement on the system throughput at different blockage densities, utilizing buffer-aided relays outperforms the traditional-relays at all densities and thresholds. For instance, a throughput of 0.1 packets per second at a higher blockage density $\lambda_b = 200 \times \lambda_s$ cannot be achieved with traditional relays for thresholds above 11 dB SNR, while this
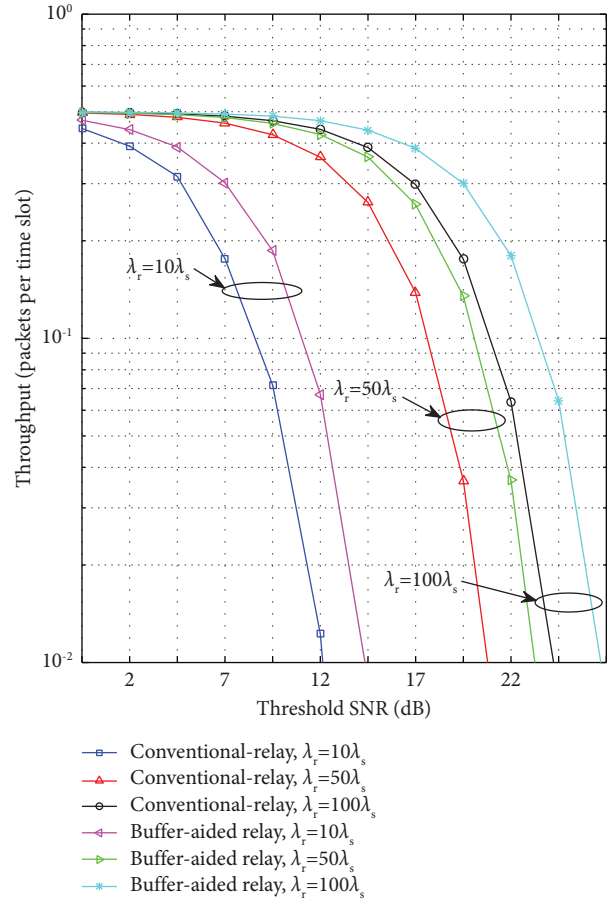
throughput can be achieved with buffer-aided relays at 14 dB SNR threshold. These thresholds of 11 dB and 14 dB can be raised to 16 dB and 19 dB, respectively, when λ_b reduced to $50 \times \lambda_s$.

Figure 5 compares the three systems from another perspective that is the relay density. Since the no-relay case will not be affected by changing the relay density, it is omitted from the comparison. It can be clearly seen that as the relay density increases, the performance of the traditional and the proposed relay-assisted mm-wave solutions is improved. For example, a throughput of 0.3 packets per time-slot cannot be achieved at SNR threshold higher than 7 dB at a low relay density $\lambda_r = 10 \times \lambda_s$, but the same throughput (0.3 packets per time-slot) is achieved at 20 dB SNR threshold if we raise the relay density $\lambda_r = 100 \times \lambda_s$. It is interesting to notice that buffer-aided relays perform very close to the traditional-relays when we reduce the relay density of the buffer-aided relays to the half while keeping the same relay density in the traditional-relay case, so rather than doubling the relay density in traditional relays to get higher throughput, we can get the same benefits by using buffer-aided relays instead of traditional relays.

Before ending this section, as shown in [20], prioritizing transmission from R to U over receiving at R from S achieves higher throughput in relays with infinite buffer-sizes.
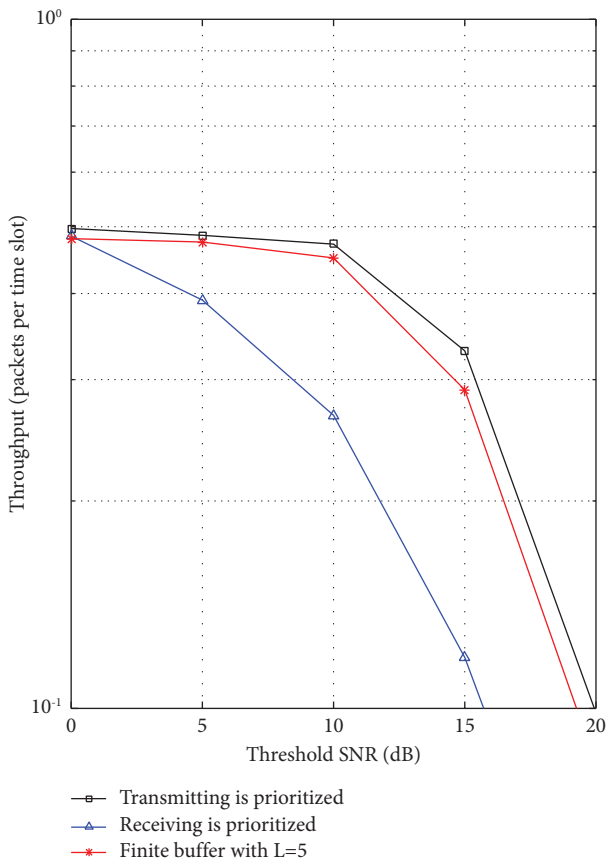
FIGURE 6: Outage probability comparison between the available solutions and the proposed solution.

Although it is not practical to assume an infinite buffer-size and it can cause unacceptable delay, we compare the system in [20] with our proposed finite buffer solution. To make it a fair comparison, we used HD relays instead of full-duplex relays used in [20], and we used a huge buffer with $L = 5000$ attempting to simulate the infinite size buffer with assuming $\lambda_b = 50 \times \lambda_s$ in both finite and infinite buffer buffer-sizes. It is obvious in Figure 6, that our proposed practical solution has a better performance than that of the infinite buffer-size when the relay transmission is prioritized over receiving, while the proposed solution has a very close performance to the infinite buffer solution when relay receiving is prioritized.

5. Conclusions

This paper proposes using buffer-aided relays in mm-wave networks with a finite buffer size. This is motivated by the capabilities of the buffer-aided relay to keep the packets until it has a good channel for transmission, while the traditional relay discards the packets that cannot be transmitted, which causes retransmission overhead. The proposed buffer-aided relay solution helps in increasing the coverage probability of the mm-wave networks, making it suitable for future IoT networks. Furthermore, the proposed system achieves higher throughput levels than the traditional-relay solution

at different blockage densities. In addition, halving the relay density while achieving the same performance is possible if we replace the traditional-relays with buffer-aided relays which is cost-effective and easier for implementation. Moreover, the proposed solution achieves 3 dB gain over the traditional solution. Finally, the proposed system can outperform the unrealistic infinite buffer-size solution. However, the selection rule for transmitting and receiving has no closed-form optimal solution to avoid the empty and full buffer problem which raises the system throughput and coverage. Machine learning is a promising technique for reaching a better selection rule in the future.

Data Availability

All required data are presented in the paper.

Conflicts of Interest

The author declares that there are no conflicts of interest.

References

[1] D. C. Nguyen, M. Ding, P. N. Pathirana et al., "6G internet of things: a comprehensive survey," *IEEE Internet of Things Journal*, vol. 9, no. 1, pp. 359–383, 2022.

[2] D. Singh, G. Tripathi, and A. Jara, "A Survey of Internet-Of-Things: Future Vision, Architecture, Challenges and Services," in *Proceedings of the 2014 IEEE World Forum on Internet of Things (WF-IoT)*, pp. 287–292, Seoul, Korea (South), March 2014.

[3] A. N. Uwaechia and N. M. Mahyuddin, "A comprehensive survey on millimeter wave communications for fifth-generation wireless networks: feasibility and challenges," *IEEE Access*, vol. 8, pp. 62367–62414, 2020.

[4] T. S. Rappaport, S. Sun, R. Mayzus et al., "Millimeter wave mobile communications for 5g cellular: it will work," *IEEE Access*, vol. 1, pp. 335–349, 2013.

[5] 3GPP, "Channel Model for Frequency Spectrum above 6 GHz," Technical report 38.900, 3GPP, France, 2016.

[6] H. Zhao, R. Mayzus, S. Sun, M. Samimi, J. Schulz et al., "28 GHz Millimeter Wave Cellular Communication Measurements for Reflection and Penetration Loss in and Around Buildings in New York City," in *Proceeedings of the 2013 IEEE international conference on communications (ICC)*, pp. 5163–5167, Budapest, Hungary, June 2013.

[7] S. Collonge, G. Zaharia, and G. ElZein, "Influence of the human activity on wide-band characteristics of the 60 GHz indoor radio channel," *IEEE Transactions on Wireless Communications*, vol. 3, no. 6, pp. 2396–2406, 2004.

[8] S. Wu, R. Atat, N. Mastronarde, and J. Li, "Coverage analysis of D2D relay-assisted millimeter-wave cellular networks," in *Proceedings of the 2017 IEEE Wireless Communications and Networking Conference (WCNC)*, pp. 1–6, San Francisco, CA USA, March 2017.

[9] I. A. Hemadeh, K. Satyanarayana, M. El-Hajjar, and L. Hanzo, "Millimeter-wave communications: physical channel models, design considerations, antenna constructions, and link-budget," *IEEE Communications Surveys & Tutorials*, vol. 20, no. 2, pp. 870–913, 2018.

[10] R. Hussain, "Shared-aperture slot-based sub-6-GHz and mm-Wave IoT antenna for 5G applications," *IEEE Internet of Things Journal*, vol. 8, no. 13, pp. 10807–10814, 2021.

[11] Y. Chen, D. Chen, Y. Tian, and T. Jiang, "Spatial lobes division-based low complexity hybrid precoding and diversity combining for mmWave IoT systems," *IEEE Internet of Things Journal*, vol. 6, no. 2, pp. 3228–3239, 2019.

[12] A. Bletsas, H. Shin, and M. Win, "Cooperative communications with outage-optimal opportunistic relaying," *IEEE Transactions on Wireless Communications*, vol. 6, no. 9, pp. 3450–3460, 2007.

[13] M. Alkhawatrah, A. Alamayreh, and N. Qasem, "Cooperative Relay Networks Based on the OAM Technique for 5G Applications," *Computer Systems Science & Engineering*, vol. 44, no. 3, pp. 1911–1919, 2022.

[14] M. Alkhawatrah, "Cooperative NOMA Based on OAM Transmission for beyond 5G Applications," *Computer Systems Science & Engineering*, 2022.

[15] S. Biswas, S. Vuppala, J. Xue, and T. Ratnarajah, "An analysis on relay-assisted millimeter wave networks," in *Proceedings of the 2016 IEEE International Conference on Communications (ICC)*, pp. 1–6, Kuala Lumpur, Malaysia, May 2016.

[16] M. Alkhawatra and N. Qasem, "Improving and extending indoor connectivity using relay nodes for 60 GHz applications," *International Journal of Advanced Computer Science and Applications*, vol. 51, no. 11, pp. 427–434, 2016.

[17] V. K. Sakarellos, D. Skraparlis, A. D. Panagopoulos, and J. D. Kanellopoulos, "Cooperative diversity performance in millimeter wave radio systems," *IEEE Transactions on Communications*, vol. 60, no. 12, pp. 3641–3649, 2012.

[18] X. Lin and J. G. Andrews, "Connectivity of millimeter wave networks with multi-hop relaying," *IEEE Wireless Communications Letters*, vol. 4, no. 2, pp. 209–212, 2015.

[19] S. Biswas, S. Vuppala, J. Xue, and T. Ratnarajah, "On the performance of relay aided millimeter wave networks," *IEEE Journal of Selected Topics in Signal Processing*, vol. 10, no. 3, pp. 576–588, 2016.

[20] C. Tatino, N. Pappas, I. Malanchini, L. Ewe, and D. Yuan, "On the benefits of network-level cooperation in millimeter-wave communications," *IEEE Transactions on Wireless Communications*, vol. 18, no. 9, pp. 4408–4424, 2019.

[21] M. Alkhawatrah, Y. Gong, O. Aldabbas, and M. Hammoudeh, "Buffer-aided 5G cooperative networks: considering the source delay," in *Proceedings of the 3rd International Conference on Future Networks and Distributed Systems (ICFNDS '19)*, pp. 1–6, Association for Computing Machinery, Paris France, July 2019.

[22] M. Alkhawatrah, Y. Gong, G. Chen, S. Lambotharan, and J. A. Chambers, "Buffer-aided relay selection for cooperative NOMA in the internet of things," *IEEE Internet of Things Journal*, vol. 6, no. 3, pp. 5722–5731, 2019.

[23] S. Luo and K. C. Teh, "Buffer state based relay selection for buffer-aided cooperative relaying systems," *IEEE Transactions on Wireless Communications*, vol. 14, no. 10, pp. 5430–5439, Oct, 2015.

[24] Z. Tian, Y. Gong, G. Chen, and J. A. Chambers, "Buffer-aided relay selection with reduced packet delay in cooperative networks," *IEEE Transactions on Vehicular Technology*, vol. 66, no. 3, pp. 2567–2575, March 2017.

[25] B. R. Manoj, R. K. Mallik, and M. R. Bhatnagar, "Buffer-aided multi-hop DF cooperative networks: a state-clustering based approach," *IEEE Transactions on Communications*, vol. 64, no. 12, pp. 4997–5010, Dec, 2016.

[26] B. R. Manoj, R. K. Mallik, and M. R. Bhatnagar, "Performance analysis of buffer-aided priority-based max-link relay selection in DF cooperative networks," *IEEE Transactions on Communications*, vol. 66, no. 7, pp. 2826–2839, July 2018.

[27] H. ElSawy, E. Hossain, and M. Haenggi, "Stochastic geometry for modeling, analysis, and design of multi-tier and cognitive cellular wireless networks: a survey," *IEEE Communications Surveys & Tutorials*, vol. 15, no. 3, pp. 996–1019, 2013.

[28] J. G. Andrews, F. Baccelli, and R. K. Ganti, "A tractable approach to coverage and rate in cellular networks," *IEEE Transactions on Communications*, vol. 59, no. 11, pp. 3122–3134, 2011.

[29] T. Bai, R. Vaze, and R. W. Heath, "Analysis of blockage effects on urban cellular networks," *IEEE Transactions on Wireless Communications*, vol. 13, no. 9, pp. 5070–5083, 2014.

[30] M. K. Samimi, T. S. Rappaport, and G. R. MacCartney, "Probabilistic omnidirectional path loss models for millimeter-wave outdoor communications," *IEEE Wireless Communications Letters*, vol. 4, no. 4, pp. 357–360, 2015.

[31] B. Xie, Z. Zhang, and R. Hu, "Performance Study on Relay-Assisted Millimeter Wave Cellular Networks," in *Proceedings of the 2016 IEEE 83rd Vehicular Technology Conference (VTC Spring)*, pp. 1–5, Nanjing, China, May 2016.

[32] R. N. James, *Markov Chains*, Cambridge University Press, Cambridge, UK, 1998.

[33] A. Berman and J. Robert, *Plemmons. Nonnegative Matrices in the Mathematical Sciences*, Society for Industrial and Applied Mathematics, Philadelphia, PA, USA, 1994.

[34] I. Krikidis, T. Charalambous, and J. S. Thompson, "Buffer-aided relay selection for cooperative diversity systems without delay constraints," *IEEE Transactions on Wireless Communications*, vol. 11, no. 5, pp. 1957–1967, 2012.

[35] R. Narasimhan, "Throughput-delay performance of half-duplex hybrid-ARQ relay channels," *IEEE International Conference on Communications*, , May 2008.

[36] A. Nadeem, M. Khojestapour, and R. Baraniuk, "Delay-limited throughput maximization for fading channels using rate and power control," in *Proceedings of the IEEE Global Telecommunications Conference, 2004. GLOBECOM'04*, November 2004.