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Multi-Connectivity-Based Adaptive Fractional Packet Duplication in Cellular Networks

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Abstract: Mobile networks of the fifth generation have stringent requirements for data throughput, latency and reliability. Dual or multi-connectivity is implemented to meet the mobility requirements for certain essential 5G use cases, and this ensures the user's connection to one or more radio links. Packet duplication (PD) over multi-connectivity is a method of compensating for lost packets by reducing re-transmissions on the same erroneous wireless channel. Utilizing two or more uncorrelated links, a high degree of availability can be attained with this strategy. However, complete packet duplication is inefficient and frequently unnecessary. The wireless channel conditions can change frequently and not allow for a PD. We provide a novel adaptive fractional packet duplication (A-FPD) mechanism for enabling and disabling packet duplication based on a variety of parameters. The signal-to-interference-plus-noise ratio (SINR) and fade duration outage probability (FDOP) are important performance indicators for wireless networks and are used to evaluate and contrast several packet duplication scenarios. Using ns-3 and MATLAB, we present our simulation results for the multi-connectivity and proposed A-FPD schemes. Our technique merely duplicates enough packets across multiple connections to meet the outage criteria.

Keywords: fade duration outage probability (FDOP); average fade duration (AFD); adaptive-fractional packet duplication (A-FPD); carrier aggregation; dual connectivity; multi-connectivity

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1. Introduction

Millimeter wave (mmWave) frequency bands have wide available bandwidths compared to the conventional cellular frequencies. They have been of great interest and a key enabler of low latency and multi-gigabit speeds for the fifth generation (5G) of cellular networks. The Third Generation Partnership Project (3GPP) introduced the new radio (NR) cellular standards and also included the mmWave spectrum due to the ultra high-throughput potential satisfying the enhance mobile broadband (eMBB) 5G use-case requirements. The optimal use of mmWave can also help reduce the control signaling overhead and improve the overall communication latency.

Much more is possible when mmWave frequencies are used in conjunction with existing Sub-6 cellular frequencies either by means of dual connectivity (DC) and/or carrier aggregation (CA). A 5G network infrastructure allows for the amalgamation of multi-network convergence and due to the explosion in the number of user equipment (UE) and access points (AP), carrier aggregation of radio resources and multi-connectivity are the means to increase the coverage and capacity. We focus on the concepts of DC and our proposed adaptive fractional packet duplication (A-FPD) scheme throughput this paper.

The mmWave inherits several challenges of its own, such as the isotropic pathloss and heavy attenuation due to blockage by common materials. This makes the wireless channel extremely vulnerable to typical non-line-of-sight (NLOS) transmission and constantly changing environmental conditions blocking the line of sight (LOS).

In order to overcome the propagation pathloss, highly directional means of communication are implemented. Appreciating the small wavelength of the mmWave, many antennas can be packed closely together to enable massive multiple input multiple output (mMIMO) diversity that, in turn, improves the link budget and range of the communication. In order to tackle the other challenge of blockage, ultra dense network (UDN) deployment is a method used to deploy more small cells reducing shadowing or no-coverage zones.

Our main goal is to design a mechanism to automatically turn packet duplication ON and OFF based off the wireless channel conditions. This is keeping in mind the trade off between the signaling required and the overall system throughput. In order to reduce the signaling overhead, we take an average of the instantaneous SINR over a certain sample size that will be consistent with the channel conditions. The major contributions of this paper are as follows:

- Utilize the available SINR as a key performance indicator to design multiple packet duplication schemes for making them more adaptive to near real time wireless channel and environmental conditions.
- Use fade duration outage probability (FDOP), in addition to SINR, to improve the network connectivity, reliability and low latency with adaptive fractional packet duplication (A-FPD).
- Attain high degree of availability using two or more uncorrelated links and only duplicate packets efficiently to not over-utilize the limited radio resources applying the proposed adaptive fractional packet duplication (A-FPD) schemes.

2. Related Work

We introduced the concept of fade duration outage probability (FDOP) and fractional packet duplication in our previous work [1] where FDOP-based handover requirements were shown in contrast to the traditional SINR-based handovers in cellular systems. A comprehensive tutorial on a newly created full-stack mmWave module incorporated into the widely used ns-3 simulator is provided by the authors in [2].

The research in [3] developed novel formulas for two-hop and three-hop relay routes and assigned a penalty cost to 10 of the three-hop paths. Then, optimization methods, such as total route and link-by-link optimization, were developed for each form of relay-selection method. Carrier aggregation and dual connectivity are presented as an implementation for the ns-3 mmWave module of the 3GPP new radio at mmWave frequencies in [4], and their integration is discussed in order to enhance the features provided by the ns-3 mmWave module.

The transient and steady-state representations of system-repair models, namely rapid and slow (i.e., crew-based) repairs for networks with a large number of repair teams, were examined in this research so that the results may be applied to real-world scenarios [5]. Often, failures are described exponentially, while ME distributions explain the more complicated recovery process.

Ref. [6] presented an empirical model to investigate the effects of handover protocols and the degree of multi-connectivity on the delay and dependability of blockage-driven wireless networks. In contrast to any typical handover enhancement method, the authors in [7] established a 'deep-mobility' model by applying a deep learning neural network (DLNN) to control network mobility. This model makes use of in-network deep learning, data analysis and prediction.

Ref. [8] discusses the mmWave area needed for the network to monitor each link's direction in addition to its power and timing. With highly directional beams and quickly changing channels, this directional tracking may be the primary barrier in achieving resilient mmWave networks. Regarding network intelligence, the authors in [9] represented handovers for public safety and emergency communications using Markov chain matrix exponential (ME) distributions, which helps make handover decisions more accurate while considering all the different factors involved in the decision process.

The authors in [10] discuss the architectural enhancements and performance analysis of packet duplication form URLLC in 5G. The authors in [11] conducted a complete in-depth survey for the horizontal and vertical handovers in heterogeneous next generation wireless networks. The authors of [12] introduced and assessed a packet-duplication system using new radio dual connectivity (NR-DC) that maximizes throughput while assuring ultra-reliable, low-latency communication.

Using queuing theory, stochastic geometry, ray-based and system-level simulations, the authors in [13] developed a novel performance evaluation methodology that considers the intricacies of mmWave radio propagation in realistic urban environments, dynamic link blockage due to human mobility and multi-connectivity network behavior to preserve session continuity. An anchor-based MC mobility model for 5G UCN environment was presented in [14] to improve user-mobility robustness. The first full end-to-end assessment of handover methods in mmWave cellular networks was presented in [15].

Multiple connectivity is investigated as a means of ensuring high dependability in industrial settings. Using actual channel data from two factories, many multi-connectivity approaches were compared [16]. Fog-RAN enabled multi-connectivity and multi-cell scheduling framework for 5G URLLC was studied in detail in [17]. Ref. [18] discusses the packet duplicating feature in 5G-NR and underlines the technical problems associated with it.

A summary of several types of MC scheduling may be found in the survey in [19]. There are primarily three types of scheduling strategies: packet duplication, packet splitting and load balancing. In order to combat the connection failures and throughput degradation experienced by cell-edge users due to their mobility, a multi-connectivity idea for a cloud radio access network was developed in [20]. The authors in [21] examined the performance analysis of packet duplication in 5G with the goal of improving the dependability of wireless links.

Two potential network designs were provided in [22] with simulation tools to test and compare their performance in order to deliver ultra-reliable services to mobile consumers by combining the LTE and mmWave radio-access technologies. The authors in [23] proposed partial packet duplication to satisfy traffic reliability requirements when dual connectivity is available to provide macro diversity. The idea is to only duplicate what needs to be completed; this utilizes potentially far fewer resources from the secondary access point. By analytically estimating the associated SNR gain, the authors of [24] demonstrated the significant transmit power decrease of multi-connectivity over single-connectivity.

Ref. [25] provided analytical research of the improvement in outage probability with multi-connectivity as well as an analysis of the resource consumption cost. In addition, the performance study was compared to standard single-connection transmission. The purpose of [26] was to provide a detailed review of the fundamental trade-offs involved in URLLC as well as the concepts that were used to develop access protocols.

Two survey papers provide overviews of multi-connectivity and cite multiple papers referring to the packet duplication; however, most are not close to our research work, which proposes a dynamic and adaptive fractional packet duplication scheme. They focus on the following different areas. Many of them discuss the Wi-Fi and LTE/5G multi-connectivity or any other multi-radio-access technology (MRAT) implementing multi-connectivity. However, these are mostly focused on the protocol portion of communication using finite sliding window network coding, redundant multipath TCP, latency control TCP, etc. Some also focus on the architectural enhancements.

Other research work has used CoMP and coordinated MIMO analysis, link scheduling optimization, or even managing the set of coordinating cells on the inter and intra frequency multi-connectivity. Other works analyze the impacts of mobility and cyclic prefix configurations in multi-connectivity scenarios and discuss the optimized SNR utilization for multi-connectivity and/or stochastic geometry with the physical layer abstraction. Some authors propose network slicing and machine learning to implement multi-connectivity but often rely on full packet duplication over the second wireless link.

The authors in [12] have very recent work on packet duplication in mobility scenarios. Furthermore, to the best of our knowledge, this is the only work that is close to our work since it involves utilizing packet duplication only when required. They compare received RSSI to a power threshold to determine how much packet duplication is utilized. If received power on one of the links is high, duplication is not used. On the other hand, we propose three different techniques—namely, SINR-difference-based, fade-threshold-based and distribution-based—to determine the amount of packet duplication. For using SINR difference, we argue that, to minimize the amount of duplication, we should only duplicate when it would be beneficial, i.e., when packets on either link could be the best. However, if one link is much stronger than another, duplication on the secondary link is not beneficial and wastes resources.

3. Multi-Connectivity in Cellular Networks

Any end user equipment (UE) in the form of a cell phone, mobile tablet, laptop computer, mobile hotspot, wireless sensor, etc. is considered to have multi-connectivity (MC) when connected to more than one base station (BS) simultaneously. Most often, this is dual connectivity (DC) with only two connections to two BS at a time. These two independent RF connections could be between the BS of the same technology or between two different technology BS, such as LTE, 5G NR, UMTS and WiFi, in conjunction with the multi-radio-access technology (MRAT) standards.

MC is also highlighted as a crucial URLLC facilitator because of its adoption to spatial diversity, in which many connections serve the UE from geographically dispersed places. In addition, time and frequency diversity are also integral to MC. Time diversity could be achieved by the means of re-transmissions and error-correction methods adhering to the delivery within the expected time interval. If in the same band, coherence bandwidth is used to separate the frequencies of various signals, or numerous frequencies are mixed for a single transmission. This may also be accomplished using carrier aggregation where data is separated over different fading channels.

3.1. Carrier Aggregation

Introduced in the advanced long-term evolution (LTE-A) standard, carrier aggregation (CA) is a means to combine together two or more carrier components (CC) to increase the transmission bandwidth capacity. This increment in capacity is achieved on the DL and the UL, with the former usually higher than the latter. The concept of carrier aggregation was first introduced in Rel 10 of the 3GPP where a maximum of five carrier components was allowed on the downlink channel.

Since then, this concept has evolved and allows multiple CA capabilities across different technologies. CA can be inter-band, meaning CC aggregation between different frequency bands, or can be intra-band, which means CC aggregation within the same frequency band. The intra-band is further categorized either as a contiguous or a non-contiguous CA, which is explained below. The CA is technically a MAC-layer split and is implemented on the physical layer.

- Inter-Band CA: As shown in Figure 1a, CCs from different frequency bands are combined together.
- Intra-Band Contiguous CA: As per Figure 1b, CCs from the same frequency band, which are adjacent to each other, are combined together.
- Intra-Band Non-Contiguous CA: As shown in Figure 1c, CCs from the same frequency band, which are non-adjacent or fairly spaced apart in the frequency domain, are combined together.

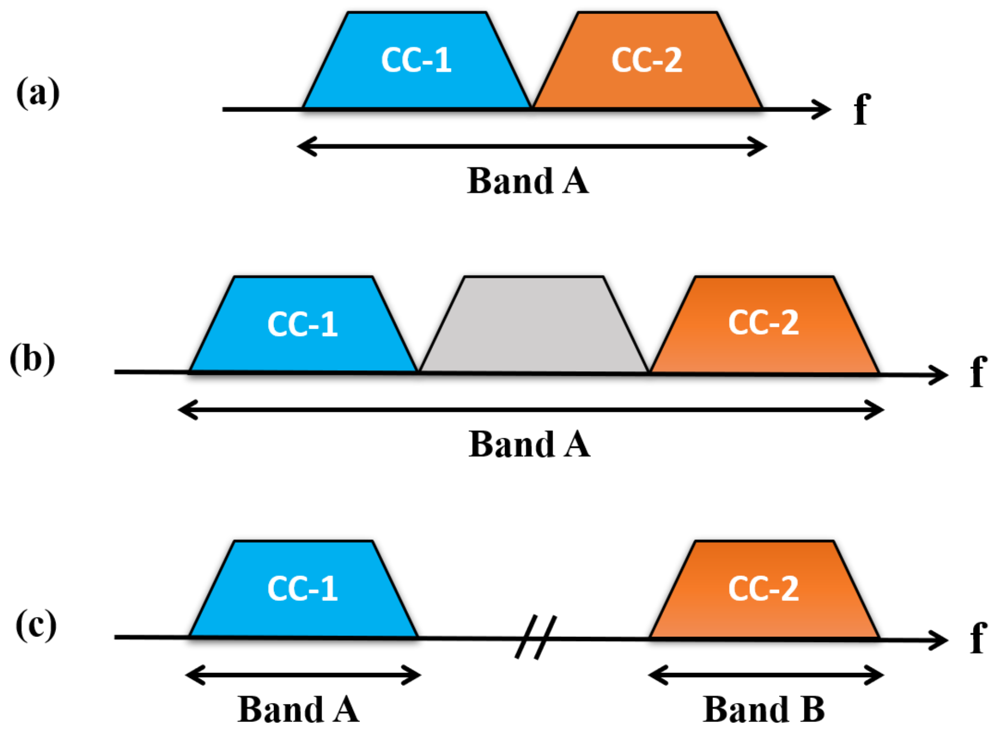

Figure 1. (**a**) Intra-Band Contiguous. (**b**) Intra-Band Non-Contiguous. (**c**) Inter-Band CA.

3.2. Dual Connectivity

Dual connectivity (DC), established in 3GPP Rel 12 standards, enables a UE to be linked to two distinct BS running on separate frequencies at the same time. CA usually uses the radio resources of the same BS and same technology but is always limited by the scarcity of bandwidth availability. DC, on the other hand, allows the mobile operators to use the abundant bandwidth resources from different BS to improve the overall user experience. DC is in charge of boosting user throughput, enhancing mobility robustness and enhancing resilience with more diversity. DC is the prime factor resulting in speedy deployment of the 5G wireless networks worldwide. DC fuels the air-interface design improvements and helps satisfy the stringent latency and reliability requirements of the new 5G use cases.

The CA feature is also deployed in addition to the DC concept, including those in the multi-radio-access technology (MRAT) environments. For example, CA of one LTE CC and one NR CC leads to E-UTRAN new radio dual connectivity (ENDC) at higher layers and an ultimate CA at the physical layer. DC can also be purely LTE based or NR based, such as the NRDC solution involving one Sub-6 NR gNB and one mmWave 5G gNB with a PDCP split. Figure 2 shows single-RAT and MRAT deployments with CA feature enablement. A UE uses DC to connect to a master eNB (MeNB) and a secondary eNB, two distinct base stations, at the same time (SeNB). Operating on distinct carrier frequencies are the MeNB and the SeNB. The master cell group (MCG) and secondary cell group (SCG), respectively, are serving cell groups connected to the MeNB and SeNB. Only UEs operating in RRC linked mode are subject to DC.

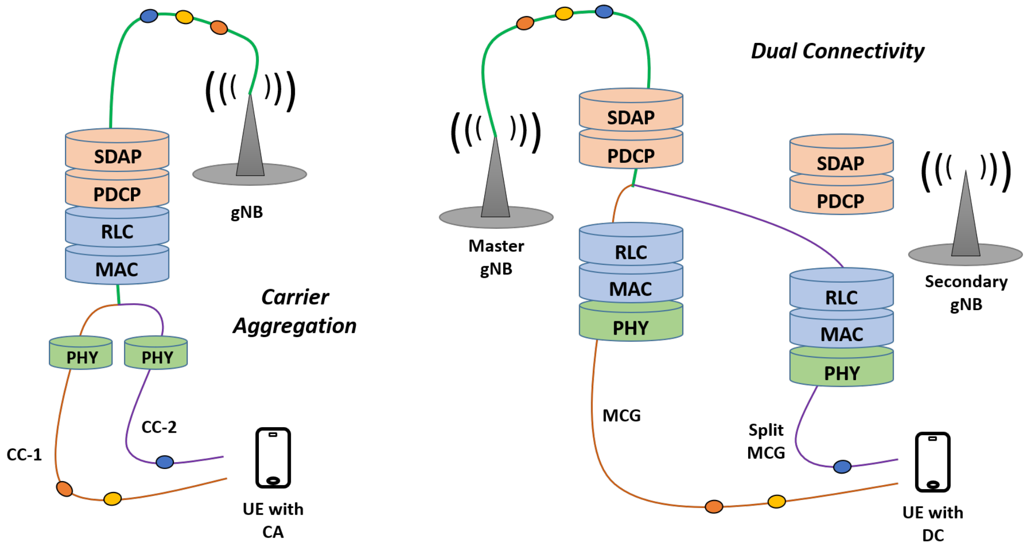

Figure 2. Carrier aggregation and dual connectivity.

3.3. Packet Duplication

Packet duplication is implemented at the packet data convergence protocol (PDCP) layer and can be performed for both the control and the data plane. With a UE having a DC, the source node is responsible for duplicating packets and sending over the two independent networks. These are then combined at the receiver with duplicate ones discarded. The split-bearer design, which is also shown in Figure 3, allows for the less invasive implementation of packet duplication in DC. The identical PDCP packet data unit (PDU) is transferred across the two distinct radio link control (RLC)/medium access control (MAC) entities or the two nodes in the PD, which is analogous to the split bearer operation.

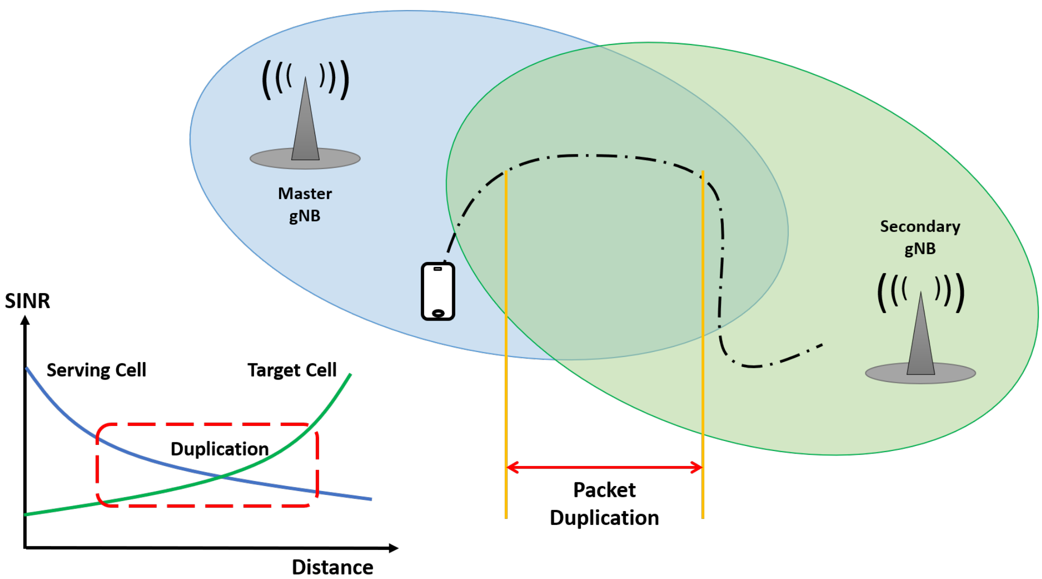

Figure 3. Adaptive packet duplication.

The radio resource configuration (RRC) layer sets up the PD operation, which is typically performed at the radio bearer level. An new RLC entity and an additional logical channel are added to the radio bearer to handle the duplicated PDCP PDUs when duplication is enabled for a radio bearer via RRC signaling. The two legs in the case of DC correspond to the MCG and SCG cell groups, respectively. Throughout the lifespan of a carrier, packet duplication is not always useful and basically depends on the channel conditions and state of the radio bearer. Thus, it is preferred to have control over whether or not packet duplication occurs. In order to save air interface resources, packet duplication must be activated or deactivated on the fly.

User data is divided into numerous carriers at the MAC layer in CA rather than DC. The RRC layer configures packet duplication in a manner similar to the DC situation. In order to manage the duplicated PDCP PDUs, an extra RLC entity and an additional logical channel are added to the original RLC entity and the logical channel associated with a radio bearer when RRC configures duplication for that radio bearer. Yet, as opposed to DC, where there are two distinct MAC entities, there is only one MAC entity. PDCP duplication on the same carrier is not supported, according to 3GPP RAN2. Hence, in contrast to the DC situation, the RRC layer must additionally set the mapping of the original and duplicate logical channels to distinct carriers. Packet duplication in CA is not supported if it has already been set up in DC according to a 3GPP RAN2 agreement.

It is worth noting that the PDCP layer in LTE already provides duplication detection based on the sequence number. As a result, if the transmitter provides multiple PDCP PDUs (through separate legs), the receiver can only analyze the earlier received PDCP PDU. The PDCP PDU that arrives later is simply discarded with no modifications to the specification required. As a result, packet duplication may be extended to the LTE-NR DC situation.

3.4. Advantages of Multi-Connectivity

In this section, we briefly discuss the advantages of using the MC/DC.

3.4.1. Enhanced Throughput

The UE receives communication over two independent RF links, and this can be fully utilized to sum up the data on both links to obtain higher throughput. In ideal conditions, this is the total theoretical value addition of the two independent throughput; however, the channel and subsequent RF conditions always have a negative impact. A challenge is often related to the delay difference between both RF paths or the out-of-order arrival of packets at the destination, which can affect the performance of upper layers, thereby, reducing the throughput.

3.4.2. Improved Reliability

Wireless medium is often termed to be a lossy medium, and re-transmissions usually make up for the reliability of wireless communications. This is time consuming and utilizes the rare radio resources, which not only affects the latency requirements but also negatively impact the data transmission on the radio links. Using MC, the re-transmissions can be reduced as packets can be sent over two channels simultaneously meeting the low-latency requirements. Spatial diversity also adds up to the reliability by reducing packet loss and error correction.

3.4.3. Robust Mobility

With MC (or DC), UE is connected to both BSs at the same time. This allows for a simultaneous control and/or user plan connectivity over two independent radio channels. DC can help reduce the interruption times during the handovers along with the amount of control signaling required. The control signaling is either already established on the secondary BS or can be moved along easily since UE has UL and DL with the primary BS. MC can help offload the overhead signaling from the core network to the radio access network (RAN) due to the existing secondary node connection.

3.4.4. Deployment Savings

With the advancement of wireless communications and the increasing number of devices requiring extremely reliable and high bandwidth connections, service providers are always attempting to improve their network's coverage and capacity. This includes deploying more BS and utilizing resources from different technologies.

The operational expense (OPEX) is very high, and a means to help transition to 5G networks is by implementing dual connectivity. This allows for existing 4G/LTE BS to work in conjunction with newer 5G-NR BS to provide better user experience. Furthermore, replacing the existing infrastructure takes many years, and MC allows for the progressive conversion to newer technology without service interruption.

3.5. Limitations of Multi-Connectivity

In this section, we describe the challenges encountered in MC operation.

3.5.1. Delay and Packet Reordering

Since UE is connected to two different RATs, the radio resource management (RRM) procedures can be different and radio link conditions can also add up to the transmission delay. The packets might very well arrive out of order at the UE. A proper packet-reordering mechanism is needed to solve this problem and avoid excessive buffering, which leads to degraded services for time-sensitive applications.

3.5.2. Cross-Layer Design

This is critical in MC as this can cause to a complete failure of achieving the primary goals. Proper information sharing is required to achieve efficient usage of network resources and flexibility. Protocol layers are different with different technologies and have unique abilities and functionalities. All network resources have to be optimally utilized, and designing a cross layer is a challenge given the multiple factors affecting the transmission over wireless channels.

3.5.3. Management of Multi-Connectivity

Networks are becoming intelligent with the evolution of software defined networks (SDN) and (network function virtualization) NFV; however, their adaption to existing cellular networks will take time. Currently, almost all of the network operators make this decision manually based on their network key performance indicators (KPI). However, the environmental conditions change, and to incorporate these manually into a network's decision making is almost impossible. Incorrect decisions on when to activate MC and when to use SC can degrade the user experience.

4. ns-3 and mmWave Module

The Network Simulator 3 (ns-3) is an open-source platform enabling the simulations of multiple different protocols for cross-layer design and analysis. Based on the already established LTE LENA platform, ns-3 has a new mmWave module that is highly modular and flexible, which helps researchers to design and validate their work. This is a full-stack implementation with multiple examples and a wide variety of test configurations, all designed using C++ [2,27]. We make use of the dual connectivity (DC) functionality on the mmWave module.

We utilize the MATLAB tool to further simulate packet traces received on the downlink (DL) and the uplink (UL) to reduce the computational overhead on ns-3. Our MATLAB code is used to precisely determine the amount of packet duplication required to maintain a certain quality of service (QoS) given the application. We can optimally turn ON and OFF the packet duplication in the environment based upon our scenarios described in further sections.

Figure 4 gives a high level representation of our simulation layout. A UE that is dual stack capable, meaning that it supports LTE as well as 5G mmWave, is moving from point A to point B. There is a building between the UE and the two bases stations. At point A, UE will have some SINR received from both BS but it is closer to and has line of sight with BS-1, so the SINR from BS-1 is stronger. As it moves, this SINR is reduced when UE is behind the building, and this is where it becomes closer to BS-2. Now, both the BS SINR are moderately lower. Finally, the BS-2 SINR becomes better as the UE crosses over the building and has line of sight with BS-2.

This is also when line of sight is established again with BS-1 improving the SINR. Our UE is always connected to two BS, and this means that the user plane connectivity is always enabled on both the RF links of the two BS. MC (or DC in our case) represents that the UE in connected mode is configured to use the available radio resources of both the BS. Thus, in case of a radio link degradation on one of the BS, the other radio link can be used for the data transmission. This helps with significantly reducing the radio link failures (RLF) and service disruptions .

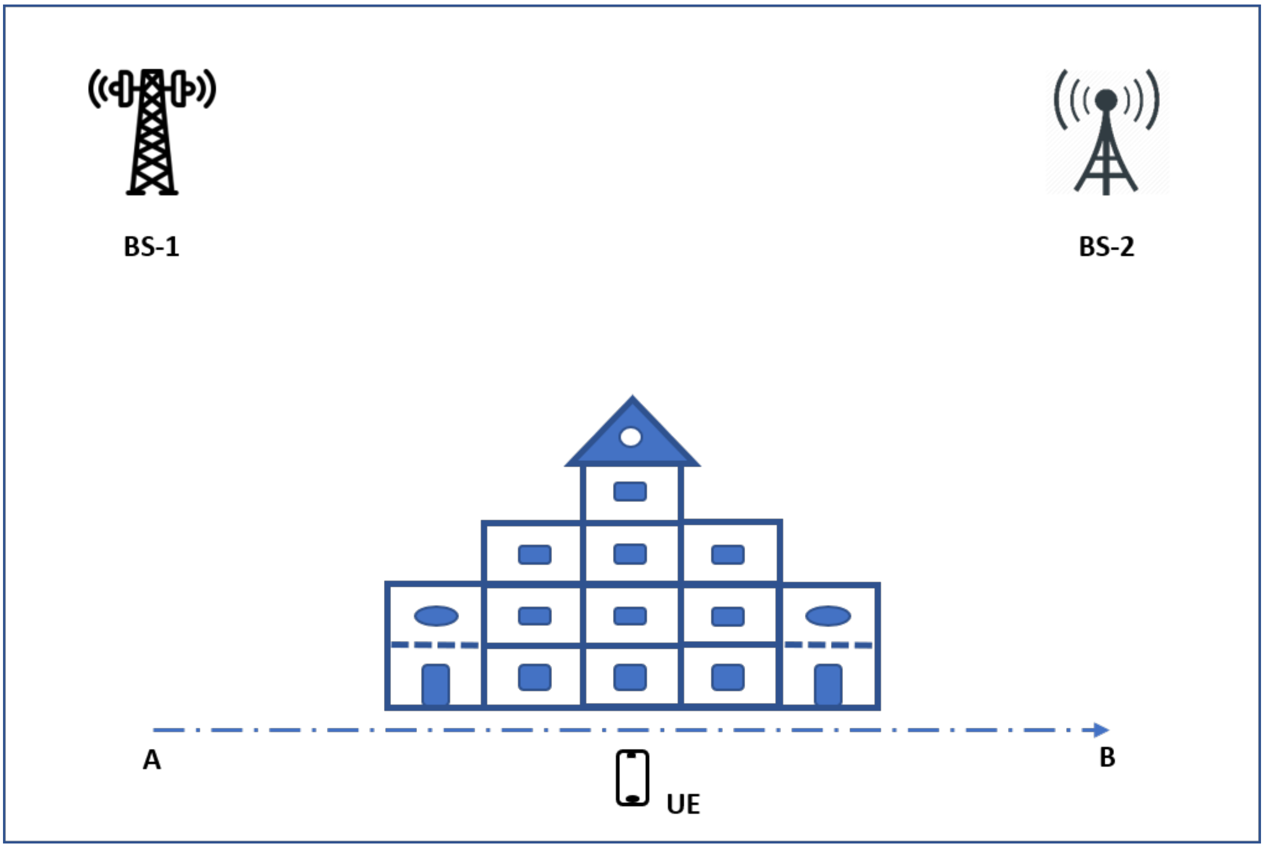

Figure 4. ns-3 simulation setupwith one UE, two base stations and one building.

Our UE is continuously measuring and reporting the SINR of both the base stations. Figure 5 shows the SINR of BS-1 received on the UE and Figure 6 shows the SINR of BS-2. We compare and select the better of the two signals at every instant, and we represent that as the best SINR. Figure 7 has the best SINR and the instantaneous SINR from the two base stations. The SINR for BS-1 varies from 50 to −30 dB, whereas the SINR for BS-2 varies between 35 and −20 dB, and the best SINR will pick the better signal of the two. The UE sends and receives data from both the base stations on the UL and DL. Not all data received on the UE is usable as some of the packets could be corrupted, and some could be completely lost due to a deep fade. Thus, we ensure that, even if the SINR is acceptable, the data received are not corrupted.

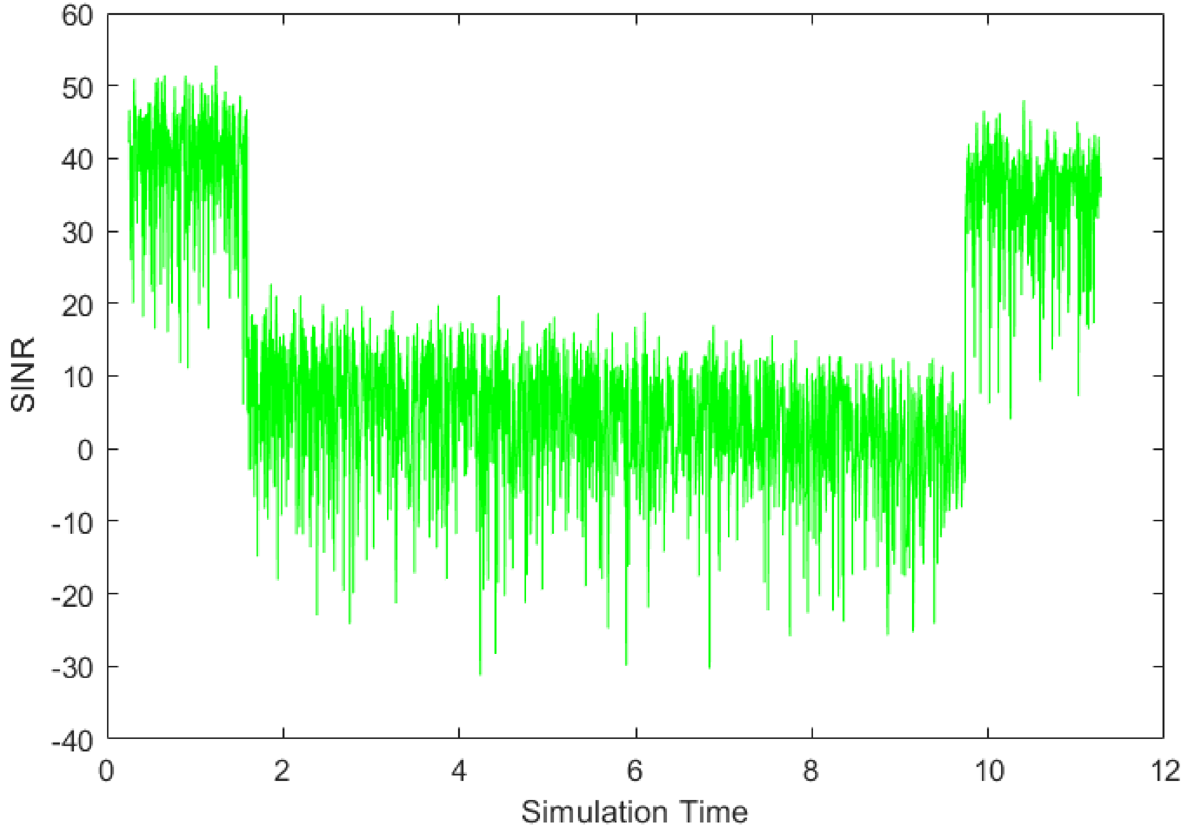

Figure 5. Instantaneous SINR of base station 1.

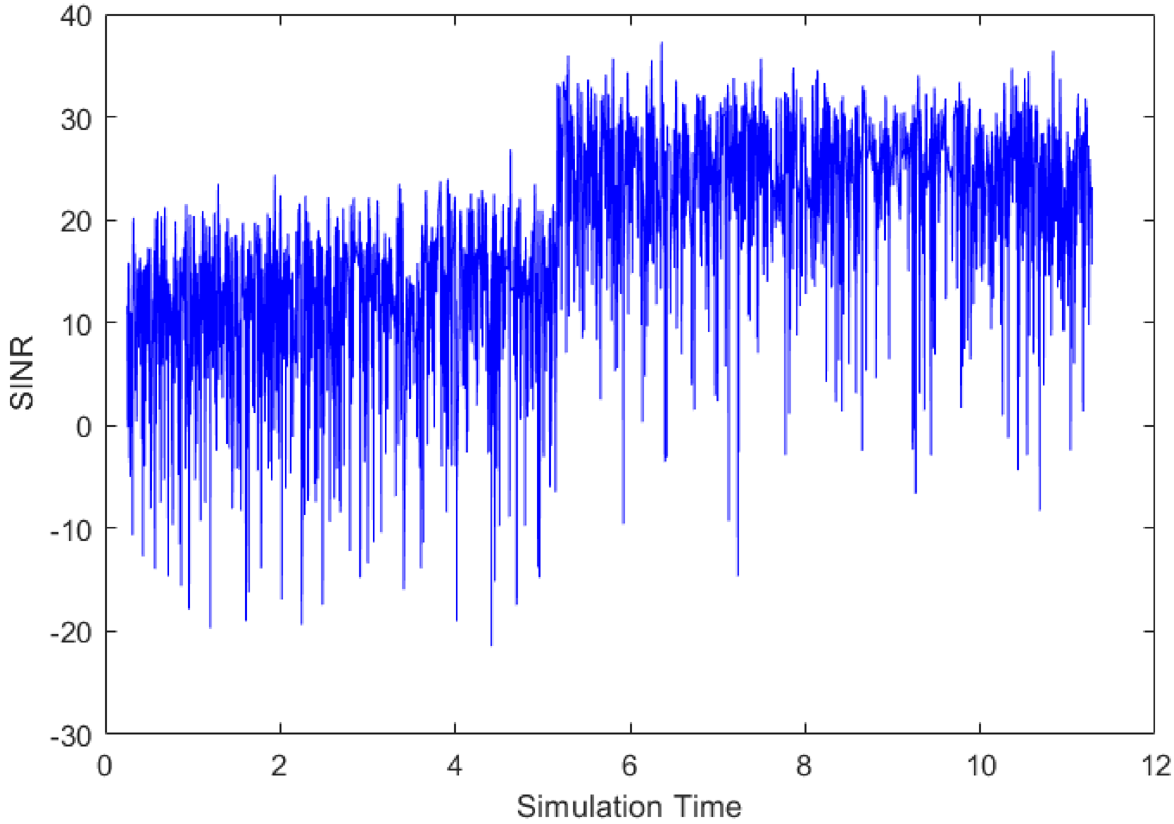

Figure 6. Instantaneous SINR of base station 2.

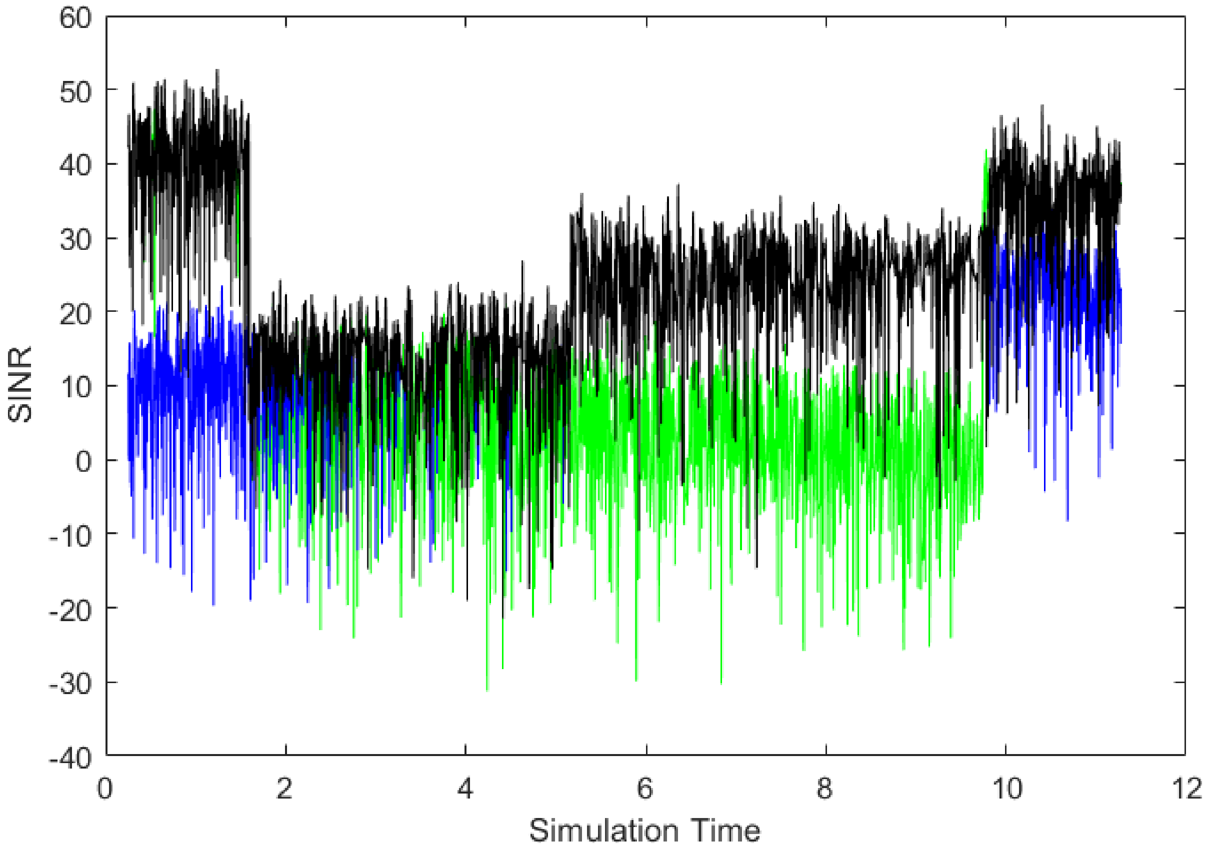

Figure 7. Instantaneous and the best SINR of the two base stations.

We discussed some of the pros and cons of packet duplication (PD) in earlier sections. Always-ON PD is a wasteful utilization of the available resources, and so we proposed adaptive fractional packet duplication (A-FPD), which will adapt to the channel conditions and duplicate packets only when necessary on the secondary RF link. We proposed multiple schemes to turn the packet duplication (PD) ON and OFF. The first scheme proposed for PD is when the SINR difference between the two base stations is under a certain predefined threshold value, called Delta. A smaller SINR difference, or Delta, means that the channel conditions for the two base stations are similar, and a higher difference means that the RF channel conditions are very different for the two base stations. Our goal is utilizing both the RF links when the SINR received from both base stations is similar or the delta is small.

Thus, we turn ON PD for a smaller delta threshold value and turn it OFF when delta is off the threshold limit. Duplicating packets with a higher delta will not be of benefit as much since one of the SINR values will be worse than the other, anything received on this worse link will be corrupt, and UE will always chose the packets received on the better SINR link.

5. Simulation Results

We take advantage of the ns-3 network simulator—in particular, the mmWave module of the simulator that was built by NYU Wireless and the University of Padua as noted before [2,27]. This module was developed specifically with the aim of simulating 5G cellular networks that are capable of functioning at mmWaves. In order to handle the 5G new radio frame structure and the 5G Numerologies, it contains specialized PHY and MAC classes. It supports carrier aggregation (CA) at the MAC layer and also supports dual connectivity (DC) with LTE BS.

We approached our adaptive fractional packet duplication schemes in three different ways as mentioned below in detail. SINR threshold or Delta SINR uses two or more RF channels to duplicate packets when their RF characteristics are not very different from each other. The second method uses the fade threshold where, if a signal drops below a certain value, packets will be duplicated on two or more RF links. The third method is distribution-based where our rate of packet duplication depends on the random exponential variable.

5.1. SINR-Threshold-Based Packet Duplication

The activation and deactivation of packet duplication requires control signaling, and if this is performed many times, a great deal of radio resources are used for the control signaling, which is against our goal of efficient utilization of RF resources. If the instantaneous SINR is to be considered to make decisions on PD, we observed that the activation–deactivation operation happens multiple times over a single data communication session. Thus, we average out the SINR over a certain sample size and then use the average SINR value for PD. This helps to reduce the number of switches and, hence, the signaling overhead. We show two sample sizes, 500 and 50, to average out the instantaneous SINR from both the BS. PD activation and deactivation for multiple delta threshold values for a average SINR sample size of 500 are shown in Figures 8 and 9. Similarly, the same is shown in Figures 10 and 11 for an average SINR sample size of 50, showing many more ON-OFF PD transitions.

Regarding the difference in SINR values, the smaller the delta threshold, the less likely is the PD as the RF channel conditions for the two base stations are different. Furthermore, a higher delta threshold means more PD. The PD will not toggle more often with higher delta but will have more switching for a smaller delta threshold, clearly showing that even an average SINR has many fluctuations over time given the unpredictable RF conditions. Figure 12 shows, for the delta SINR on the x-axis, how much reduction in corrupt packets can be achieved with PD. We also show how much of the actual packet duplication is required to reach this number. For example, 35.38% packet duplication is required to have 5.45% corrupt packets in the overall communication.

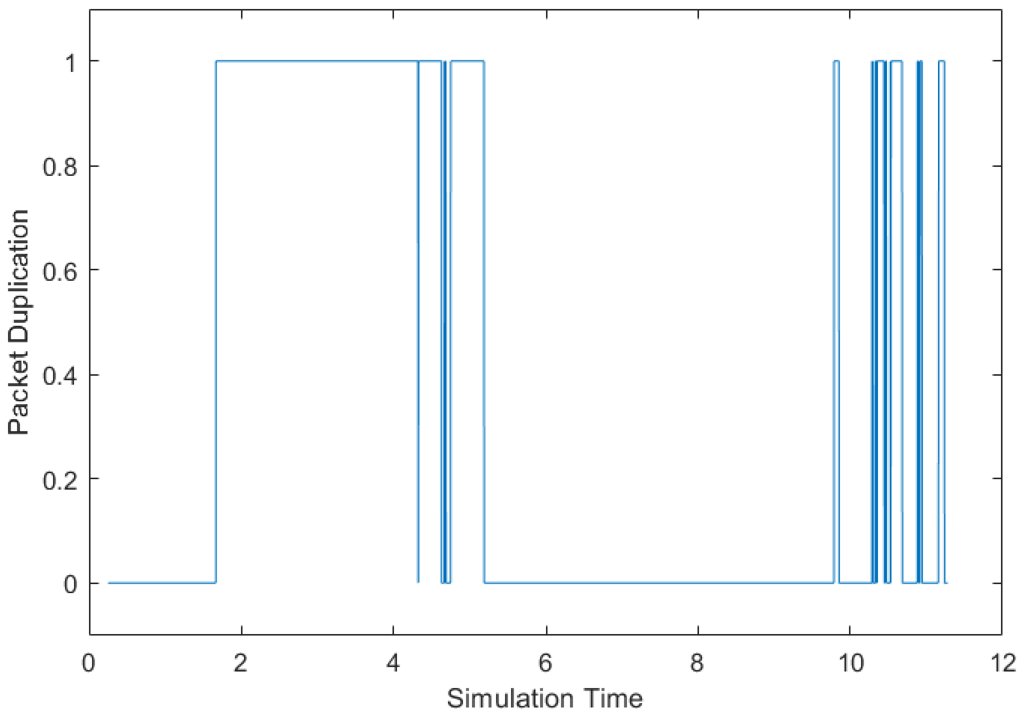

Figure 8. Packet Duplication with an average (500 sample size) SINR difference of <=10 dB.

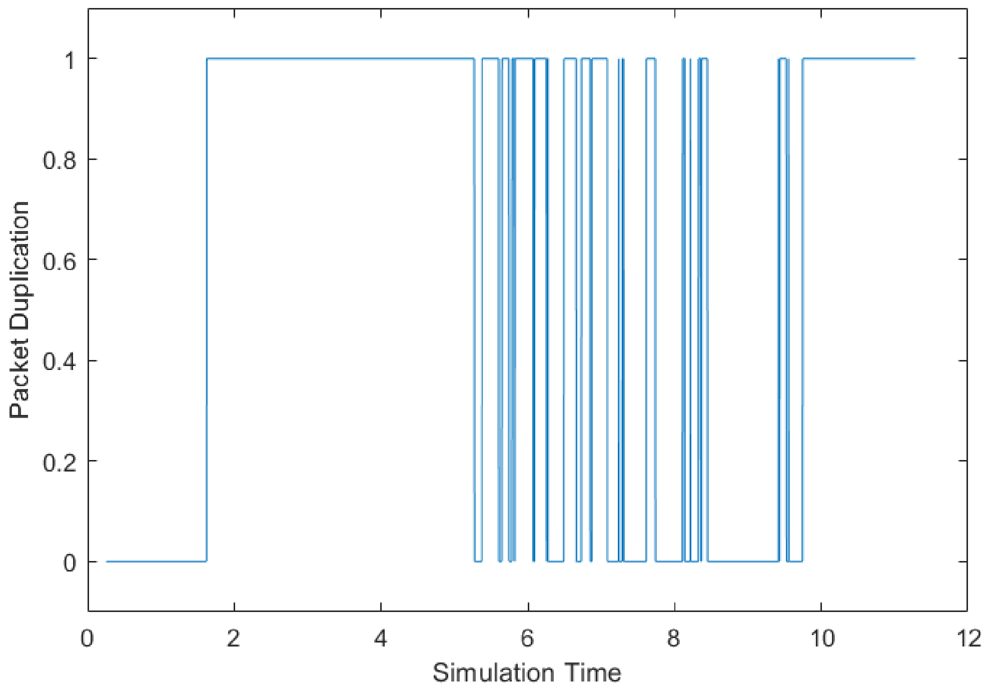

Figure 9. Packet Duplication with an average (500 sample size) SINR difference of <=20 dB.

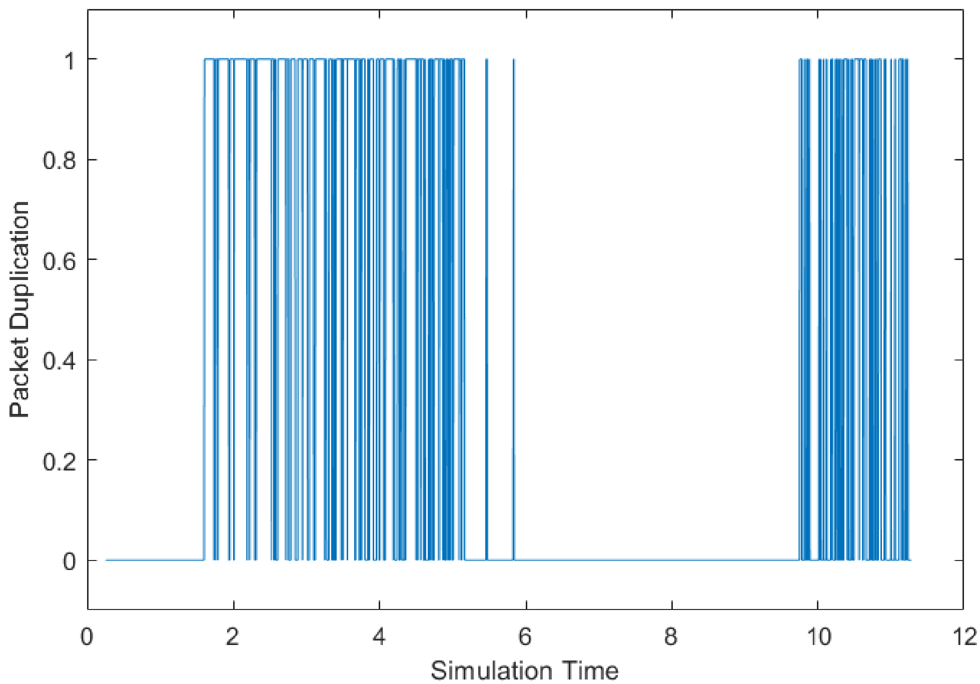

Figure 10. Packet Duplication with an average (50 sample size) SINR difference of <=10 dB.

This amount of PD increases in order to achieve minimum corrupt packets. In contrast to the average SINR with a sample size of 500, we simulate the environment using an average SINR with a sample size of 50, and the chart is shown in Figure 13. The average SINR with a sample size of 50 has more fluctuations than the average SINR with a 500 sample size, and the PD switching happens many more times. Figure 14 shows the number of times that packet duplication was triggered for the average SINR with sample sizes of 500 and 50 for the two base stations.

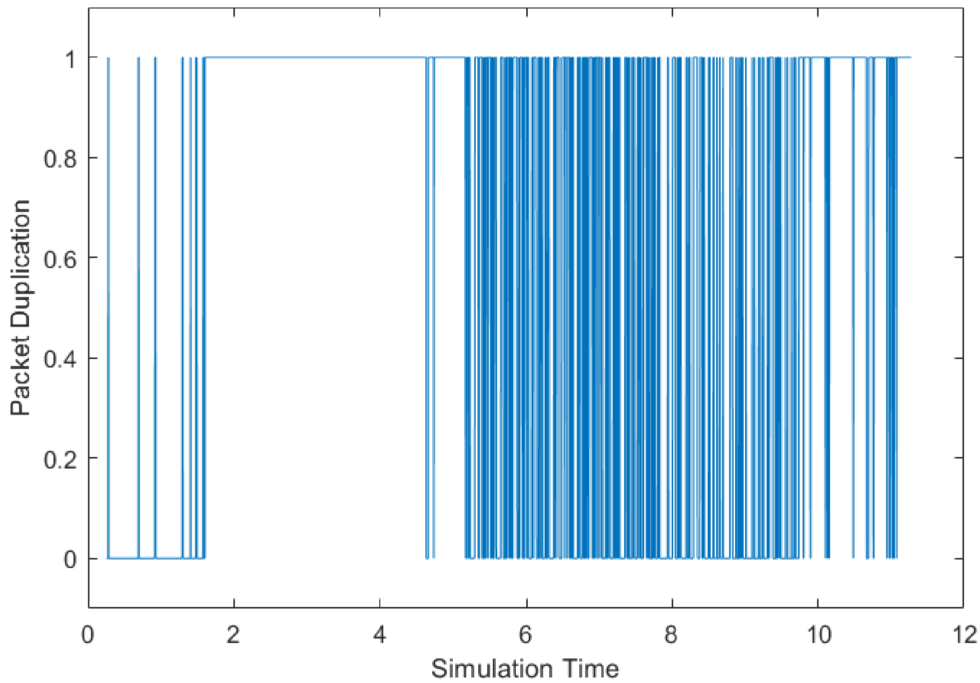

Figure 11. Packet Duplication with an average (50 sample size) SINR difference of <=20 dB.

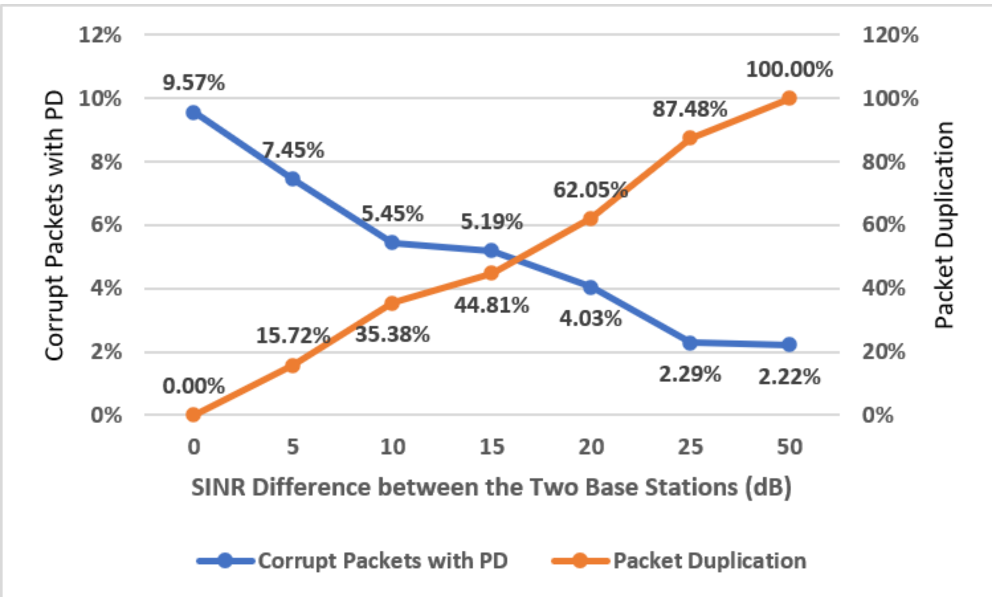

Figure 12. Difference in the average SINR-based (500 sample size) Packet Duplication.

Our results above can be used to understand the wireless channel conditions in regard to the re-transmissions involved for the corrupt packets versus the packet duplication rate required to compensate for the corrupt or the lost packets. A service provider or an operator can then decide what action to take based on the available resources. We provided an approach to find the optimal PD rate given the reduction in the percentage of the corrupt packets.

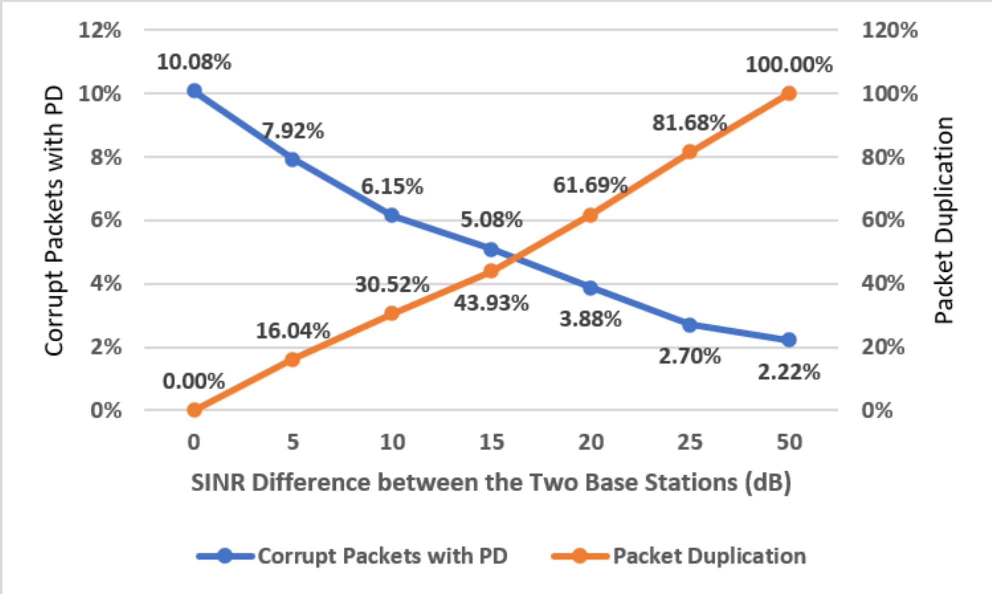

Figure 13. Difference in the average SINR-based (50 sample size) Packet Duplication.

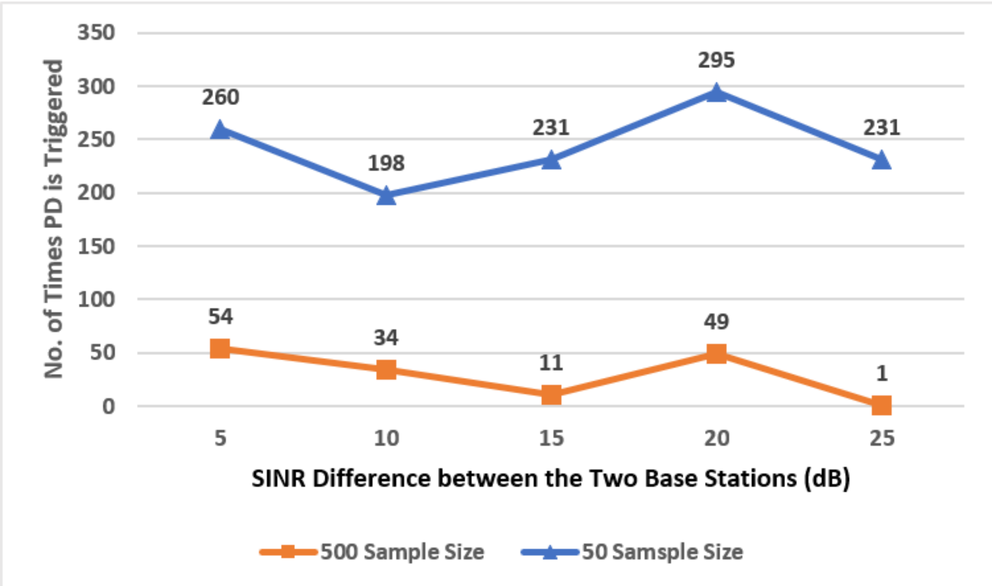

Figure 14. Actual number of times that Packet Duplication is triggered.

As shown in Table 1, for every SINR difference in dB, we have columns for 500 samples and 50 samples. Each of these values are the difference of the 10-times relative decrease in corrupt packets and the percentage increase in packet duplication. For example, from 5 to 10 dB for a 50 sample size, a 1.77% decrease in corrupt packets was observed for 14.48% of additional packet duplication. This gives us -3.22%, which is the difference of 14.48% and 17.70%. Similarly, we calculated values for all others to determine the pattern where this difference then becomes positive.

Table 1. Relative decrease in the % corrupt packets vs. % increase in Packet Duplication.

SINR Difference (dB)	500 Samples	50 Samples
5	−5.48%	−5.56%
10	−0.34%	−3.22%
15	6.83%	2.71%
20	5.64%	5.76%
25	8.03%	8.19%
50	11.82%	13.52%

In addition to the original scenario explained above that we extensively used to evaluate even more methods (5.2 and 5.3) to determine the activation and de-activation of packet duplication, we present a few more scenarios using the Delta SINR method. Our original scenario consisted of a single building that acts as an obstacle to our dual stack UE, which moved from point A to point B. Now, we add three more scenarios to evaluate and analyze the results in Table 2, which are very similar to the original scenario to help support our proposed A-FPD method.

In the second scenario, the dimensions of the building are changed, and as a result, the attenuation from the two BSs is reduced to a certain extent. The third scenario has two buildings placed very close to each other, and finally the fourth scenario has two buildings fairly distant from each other. All these four scenarios, including the original, are for the SINR difference of 10 dB between the two BSs. The movement of the UE is the same to better understand the impact of the environmental changes on the packet-level UE performance.

Another criterion is added to validate the uniformity of all four scenarios where we consider a hard handover instead of dual connectivity. This is where the UE will always hand off to the stronger signal BS and will have single connectivity at all times. The respective corrupt packet percentages are shown as compared to a standard adaptive fractional packet duplication approach. This is shown in Table 2 where the first row is for the A-FPD approach with a SINR difference of 10 dB, and the second row is the single connectivity hard handover approach. In all cases, the Delta SINR method produced a lower corrupt packet percentage, so the average values over the four scenarios certainly show lower percentage of corrupt packets. Furthermore, this was only when duplicating packets when the SINR values were close (with 10 dB) for both links, duplicating 35.38% as shown in Figure 12.

Table 2. Average of the multiple scenarios using Adaptive-Fractional Packet Duplication and hard handover for a 10 dB SINR difference.

Average	Original Scenario	Second Scenario	Third Scenario	Fourth Scenario
6.73%	5.45%	7.19%	6.03%	8.23%
10.23%	11.21%	8.03%	9.04%	12.65%

5.2. Fade-Threshold-Based Packet Duplication

As discussed earlier, the fade duration outage probability (FDOP) defines a time over which a communication will fail if a fade persists too long. As per Figures 5 and 6, the average SINR with a smaller sample size of 50 shows very drastic changes over a very small interval of time. If the SINR falls below a certain minimum acceptable value, any packets transmitted over that time interval could be either corrupt or completely lost. This fading of the signal below a certain threshold value is used to decide whether or not the packets will be duplicated. Figures 15 and 16 show the packet duplication operation for the different fade threshold values used in our simulation for an average SINR sample size of 500. Figures 17 and 18 represent the very same information for an average SINR sample size of 50.

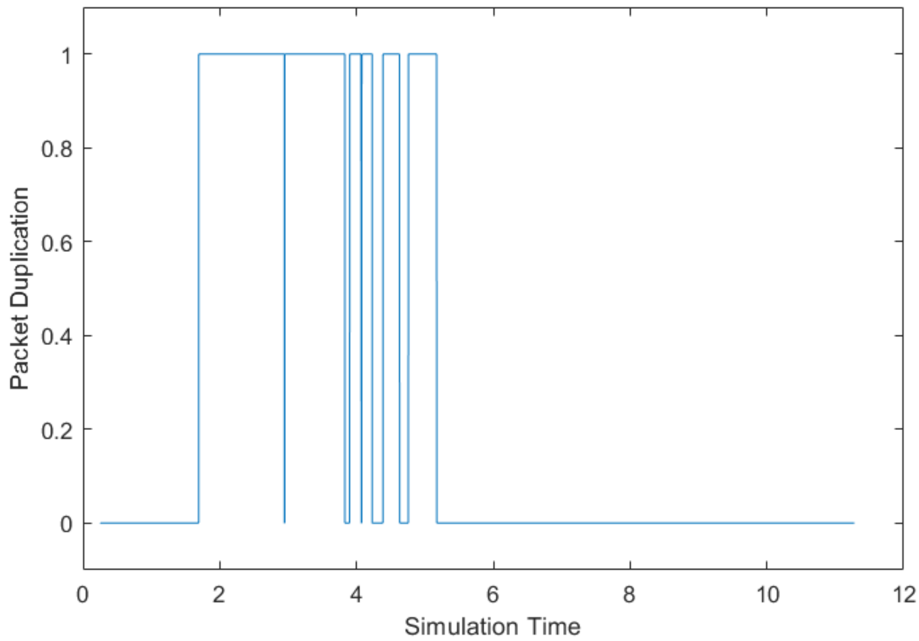

Figure 15. Packet Duplication with an average (500 sample size) fade threshold of 15 dB.

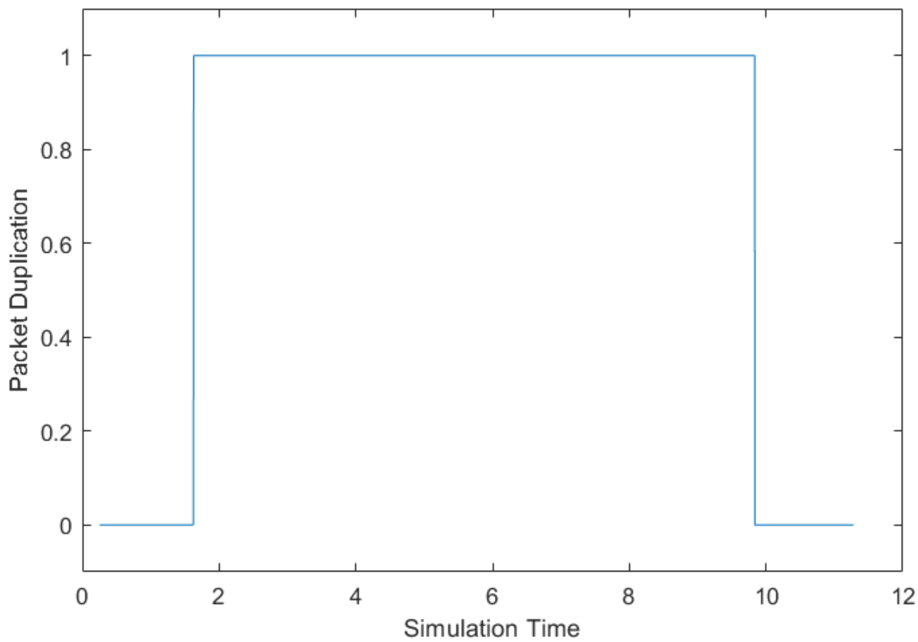

Figure 16. Packet Duplication with an average (500 sample size) fade threshold of 30 dB.

Figure 19 shows, for the fade threshold on the x-axis, how much reduction in corrupt packets can be achieved with PD. We also show how much of the actual packet duplication is required to reach this number. For example, 52.52% packet duplication is required to have 4.05% of corrupt packets in the overall communication. This amount of PD increases in order to achieve the minimum corrupt packets. This also means more radio resource utilization. In contrast to the average SINR with a sample size of 500, we simulate the environment using the average SINR with a sample size of 50, and the chart is shown in Figure 20. The average SINR with a sample size of 50 has more fluctuations than the average SINR with a sample size of 500, and PD switching happens many more times.

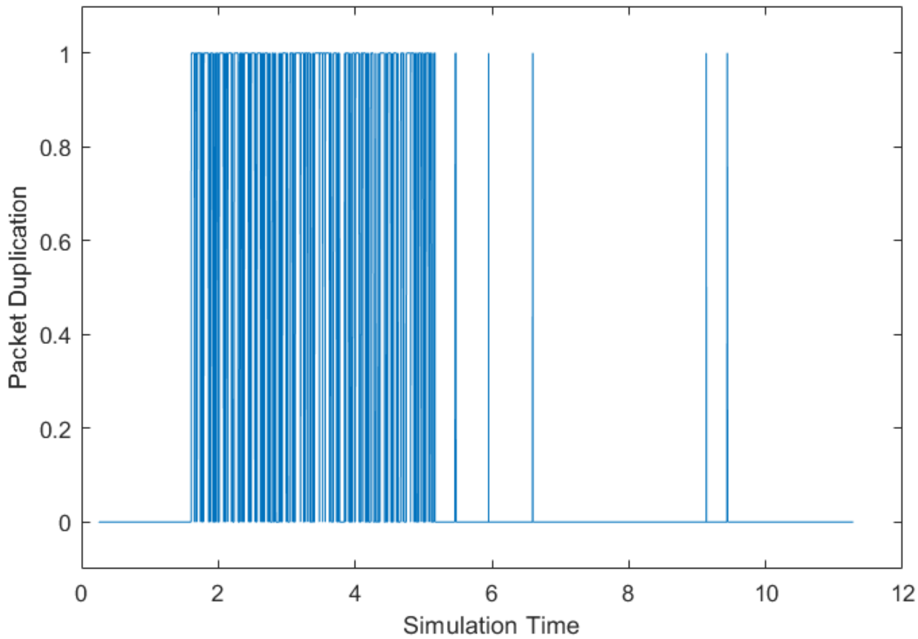

Figure 17. Packet Duplication with an average (50 sample size) fade threshold of 15 dB.

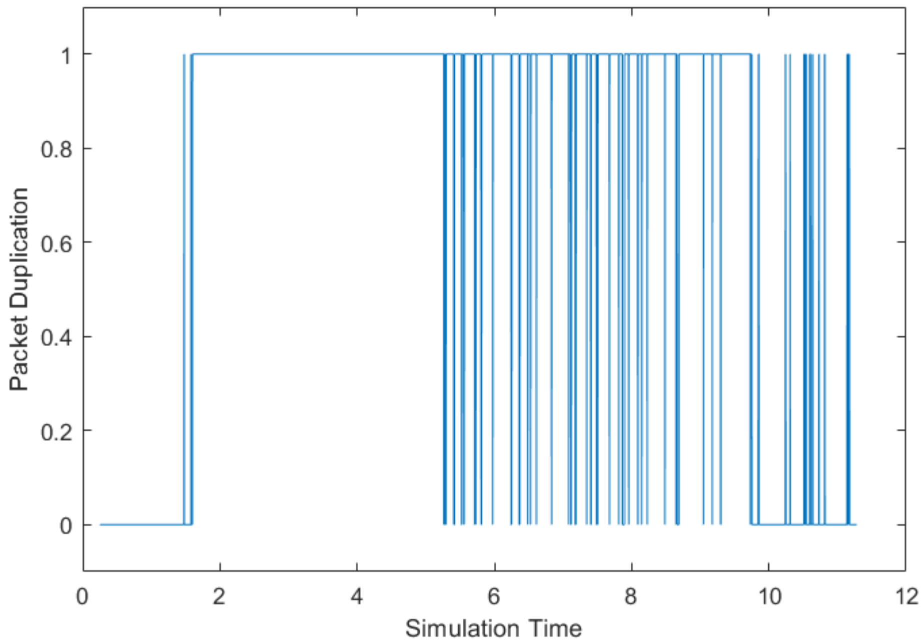

Figure 18. Packet Duplication with an average (50 sample size) fade threshold of 30 dB.

Figure 21 shows the number of times that packet duplication was triggered for the average SINR with sample sizes of 500 and 50 for the two base stations. As shown in Table 3, for every fade threshold in dB, we have columns for 500 and 50 samples. Each of these values are the difference of the 10-times relative decrease in corrupt packets and the percentage increase in packet duplication. For example, from 20 to 25 dB for a 500 sample size, a 1.33% decrease in corrupt packets was observed for 20.12% additional packet duplication. This gives us 6.82%, which is the difference of 20.12% and 13.30%. Similarly, we calculated values for all others to determine the pattern where this difference then becomes positive.

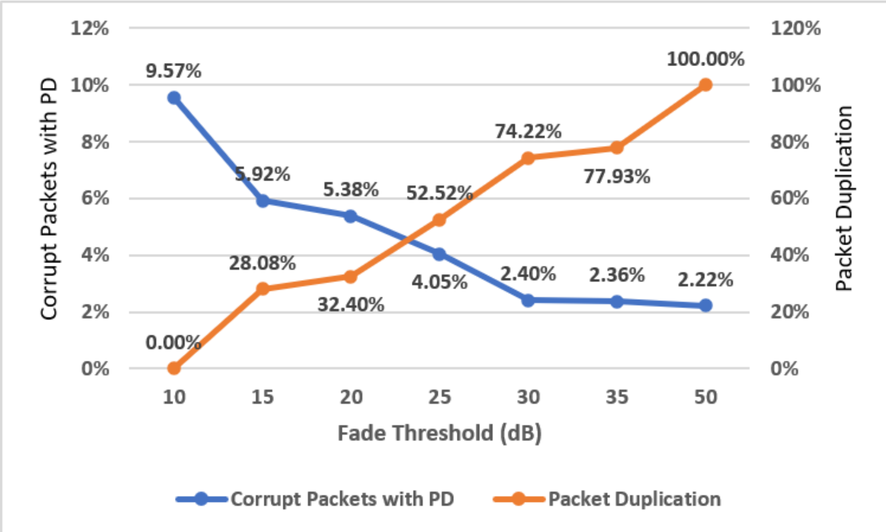

Figure 19. Fade-threshold-based (500 sample size) Packet Duplication.

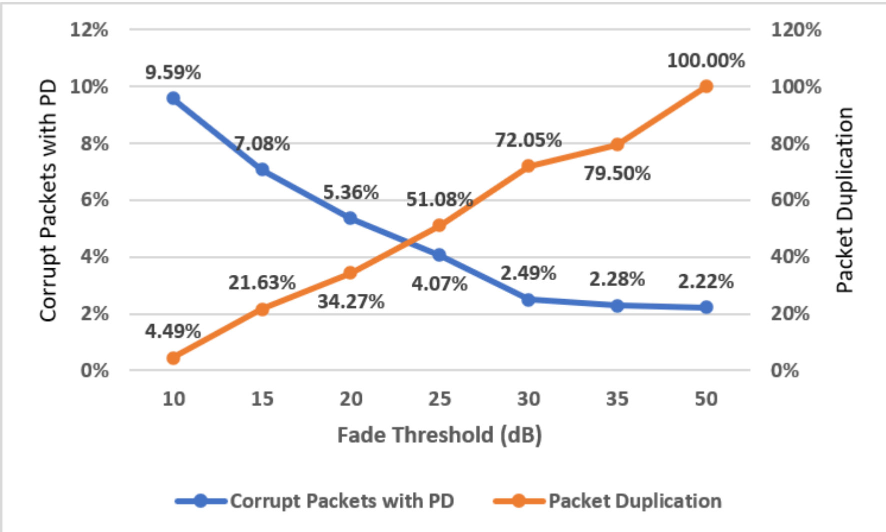

Figure 20. Fade-threshold-based (50 sample size) Packet Duplication.

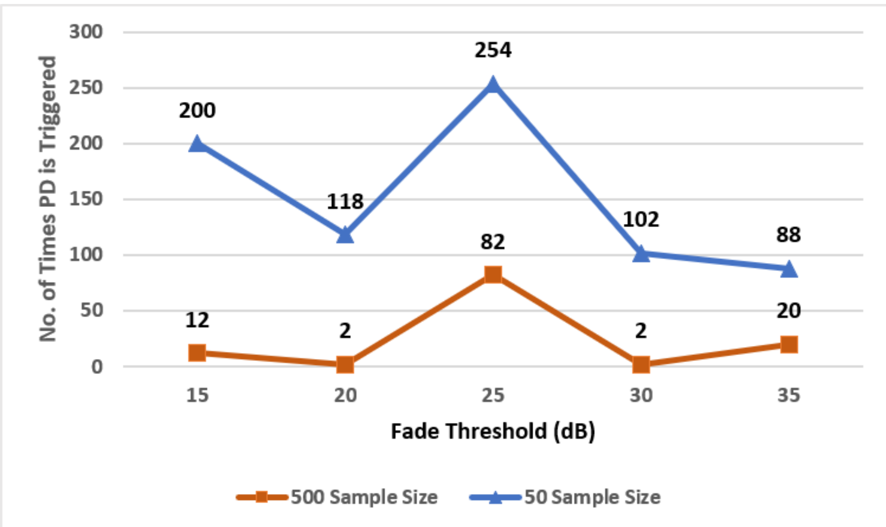

Figure 21. Actual number of times that Packet Duplication is triggered.

Table 3. Relative decrease in the % corrupt packets vs. % increase in Packet Duplication.

Fade Threshold (dB)	500 Samples	50 Samples
5	−8.42%	−7.96%
10	−1.08%	−4.56%
15	6.82%	3.91%
20	5.20%	5.17%
25	3.31%	5.35%
50	20.67%	19.9%

5.3. Distribution-Based Packet Duplication

We selected exponential random variables to decide the rates of enabling and disabling the PD. We turned the PD ON and OFF randomly based on our exponential rates [23]. If both BS and UE agree on the random number generator and seed, then, theoretically, there would be no signaling overhead to turn ON and OFF the PD. This can also be termed as a zero-signaling mechanism. An advantage of our method is that the UE and BS would be more aware of the event occurrences since random ON and OFF choices can always be studied, and required resources can always be made available beforehand. As shown in Figure 22, the exponential random rate of starting duplication is plotted on the x-axis, and the exponential random rate of stopping duplication is plotted on the z-axis.

The 3D plot shows how the packet duplication is impacted due to the coordination on these two exponential random variables impacting the PD ON and OFF rates. A 100% PD is achieved when the log of the starting duplication rate is about 2.5 (rate equals $10^{2.5} = 316$ starts per second) and corresponding log of the stopping duplication rate is at -0.5 (rate equals $10^{-0.5} = 0.32$ stops per second). The reverse is for the 0% PD where the log of the starting duplication rate is about -0.5 and the corresponding log of the stopping duplication rate is at 2.5.

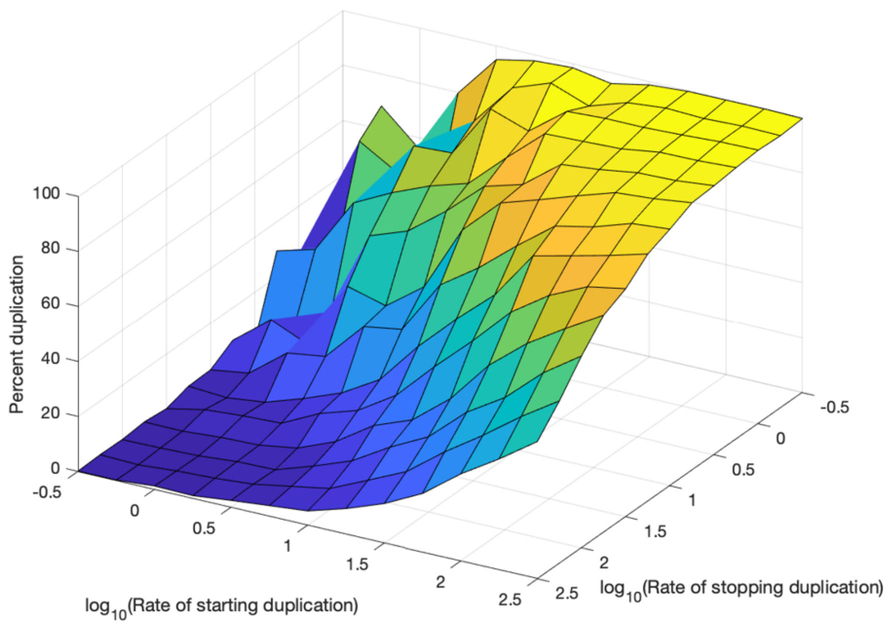

Figure 22. Packet Duplication based on exponential random variable.

The corresponding corrupt packets are shown in Figure 23. Similar to the above plot, a lower starting duplication rate along with a higher stopping duplication rate yields over 9% corrupt packets. Furthermore, a maximum starting duplication rate with a lower stopping duplication rate provides a corrupt packet percentage close to 2%. Lastly, Figure 24 shows the number of times PD is triggered in the entire communication. It can be clearly seen that, when both the starting duplication and stopping duplication rates are high, the number of switches is also high.

The PD switches are the lowest when both these rates are at their lowest. This study can be used to understand and analyze the RF channel, and the actual amount of PD can be determined. In this study, we used the same mean starting and stopping rates throughout the simulation. However, as seen Figure 7, the mean SINR values change over the course of a simulation when affected by buildings and distance. In [23], the best starting and stopping rates are based on the average SINR. Thus, it would be advantageous in practical applications to have some adjustment of the starting and stopping rates over time; however, these would change infrequently.

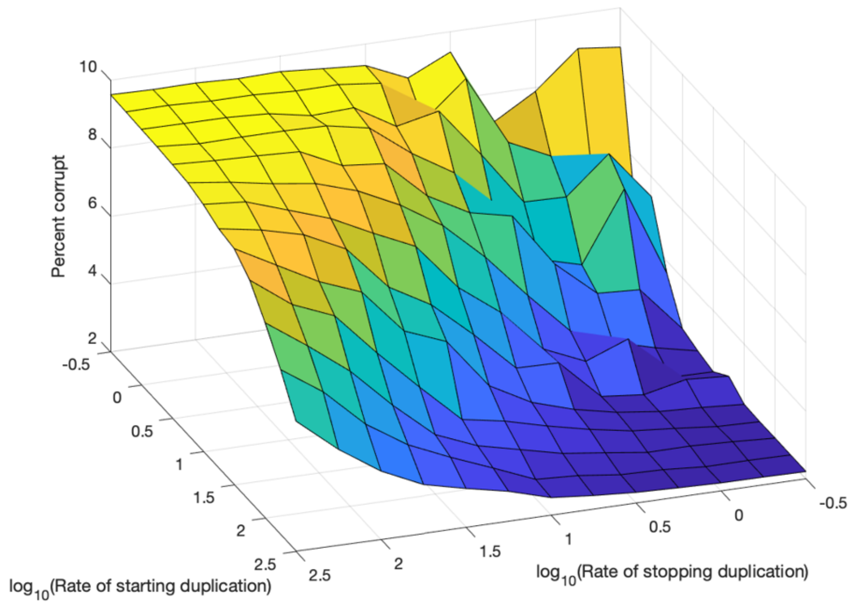

Figure 23. Corrupt Packet Duplication based on an exponential random variable.

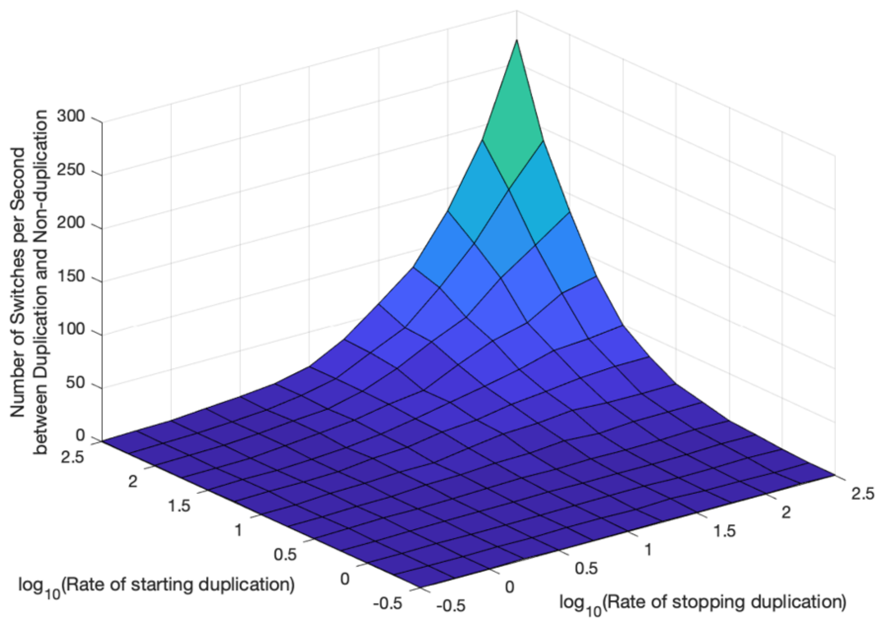

Figure 24. Actual number of times that Packet Duplication is triggered.

6. Conclusions and Future Work

Radio resources are very limited and need to be efficiently used to meet the reliability and low-latency requirements in 5G. Multi-connectivity adds spatial diversity but also helps with beam forming and massive-MIMO in the case of mmWave connections. Our proposed adaptive fractional packet duplication scheme allows for flexibility in the network to turn ON and OFF the PD.

Our multiple schemes using the SINR or fade threshold were the most effective as they required small changes in real network algorithms. Since a complete PD is wasteful over the entire transmission time, all our simulation results clearly show when and where PD is effective and help to clearly understand the channel conditions. A network operator can, thus, decide on PD depending on the resource availability and application requirements. Future work can include more than two connections and can also include the WiFi6 standards to improve data rates and help with cellular network offloading.

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