Random Access in Millimeter-Wave Beamforming Cellular Networks: Issues and Approaches

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ABSTRACT

The mmWave band has been utilized for indoor applications in IEEE 802.11ad and for point-to-point wireless backhaul solutions. Very recently, mmWave communications has come into the spotlight as an enabling technology for 5G *cellular networks* by virtue of development of mmWave beamforming technology and channel measurement campaigns in outdoor environments driven by academia and industry. A high path loss in the mmWave band can be alleviated by adaptive beamforming using antenna arrays; aligning transmit and receive beams in direction can result in high beamforming gains. When we consider the cellular network in the mmWave band, random access, which is primarily used for initial access and handover, is the very first issue in system design. Since random access cannot fully benefit from beamforming due to the lack of information on the best transmit-receive beam pair, the design of the random access channel, RACH, becomes more challenging, especially in non-line-of-sight channels. In this article, we analyze fundamental issues of RACH in mmWave cellular communications and present possible approaches to address these issues. Furthermore, research challenges and future directions are discussed.

INTRODUCTION

In recent years, mobile data traffic has been dramatically increased and is expected to continue its growth. To cope with the growing demand on mobile traffic, a radio access technology needs to be enhanced by improving spectral efficiency, increasing frequency bandwidth, or increasing cell density. However, the spectral efficiency of point-to-point communication is close to the theoretical limit. Cell densification has difficulty handling a large amount of intercell interference since cells may be deployed in an unplanned manner, and the signaling for interference management is limited by non-ideal backhaul links of networks. Taking the aforementioned challenges into account, a straightforward way to deal with the traffic demand is to increase bandwidth for communications. In this sense, the millimeter-wave (mmWave) band is recently being considered as one of promising bands for cellular networks [1] since abundant contiguous frequency resources are available, while the frequency bands under 5 GHz are very fragmented and crowded.

Among the differences of propagation characteristics between legacy cellular bands under 5 GHz and mmWave bands (e.g., 28, 38, 60, and 70 GHz), the most notable one is the path loss difference. When isotropic antennas are considered at the transmitter and receiver sides, the path loss in free space increases by the frequency squared. Moreover, the penetration loss at mmWave bands is larger than that at legacy cellular bands. On the other hand, a large number of antenna elements can be packed into a small form factor in mmWave bands due to the much smaller wavelength than legacy cellular bands. Hence, the severe path loss of the mmWave bands can effectively be alleviated because a high beamforming gain is obtained using a large number of antenna elements. Moreover, a massive multiple-input multiple-output (MIMO) system [2], where hundreds of antennas are implemented at a base station (BS), becomes more feasible and can be useful for transmitting signals over a long distance in the outdoor environment. In [3], a beamforming algorithm for mmWave cellular communications is presented. The results of extensive propagation measurement campaigns in indoor and outdoor environments are shown in [4, 5]. By virtue of the beamforming technique and the propagation measurement results, the mmWave cellular network is being considered as a candidate technology for fifth generation (5G) mobile broadband.

To fully exploit the beamforming gain, the beam direction should be well aligned with the direction of the propagation path. The conventional way to find the best beam direction is to utilize the reference signal for beam quality estimation and exchange the information about the best beam direction between a BS and a mobile station (MS), as in IEEE 802.11ad protocol. This method will work well when the MS has a connection with its serving BS; that is, control signals conveying the beam index can be transmitted through an established radio link.

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However, there are circumstances when communication using the best beam pair may not be feasible. More specifically, when the MS accesses the network initially using a random access channel (RACH), the best beam pair cannot be known a priori. Hence, it is difficult to set the beam directions at both the MS and BS for RACH preamble transmission and reception, respectively. Since the RACH is also used for important procedures such as handover in cellular networks, the RACH design is a critical issue that needs to be resolved first.

In this article, the random access procedure in traditional cellular networks is reviewed, and the important issues in designing RACH for mmWave cellular networks are analyzed. To address those issues, possible approaches are presented, and research challenges are discussed. The random access issue in mmWave beamforming cellular systems, to the best of our knowledge, has not been thoroughly investigated in the literature yet.

Random Access in Traditional Cellular Networks

In this section, we review random access in traditional cellular networks to better understand the related issues of random access in mmWave cellular networks. In a cellular network, an MS needs to establish a radio link with a BS for data transmission and reception. To establish the radio link, the MS first acquires synchronization in downlink and then accesses the network using the RACH, as in Long Term Evolution (LTE) standard [6]. The RACH can be used for various purposes: *initial access*, *handover*, *maintaining uplink synchronization*, and *scheduling request*. Among these various purposes, we focus on initial access and handover. In general, the random access procedure consists of four steps, as illustrated in Fig. 1. In the first step, the MS randomly selects one among a set of preamble signatures. The selected preamble is transmitted from the MS to the BS using the time-frequency resources indicated in the system information broadcast by the BS. In the second step, if the BS successfully detects the random access preamble, the BS transmits the random access response (RAR), which includes the index of the detected preamble sequence, the uplink timing information, and the indication of the resource allocation for the next step. In the third step, the random access message, including the identity of the MS, is transmitted from the MS to the BS. Finally, the identity of the MS is transmitted from the BS to the MS, confirming that the random access procedure is successfully completed for the MS. In the remainder of this article, we focus on the first step in which the preamble is transmitted from the MS and detected at the BS.

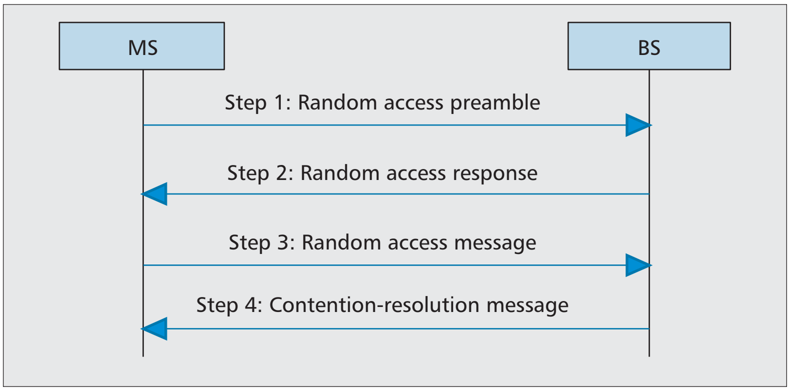

Figure 1. The random access procedure in legacy cellular networks.

MmWave Beamforming Cellular Networks

In an mmWave cellular network, highly directional beamforming is used at both the BS and MS, unlike the traditional cellular network. By virtue of very small wavelengths ranging from 1 to 10 mm in the mmWave bands, a large number of antenna elements can be packed into a small device. However, due to the high cost and complexity of hardware implementation, it is feasible to have only one or a few digital chains, each connected to a set of antenna elements that forms an analog beam. The transmitter selects a transmit beam pattern, which determines the phase shifter weights to steer the beam in a certain direction. Similarly, the receiver selects a receive beam pattern to receive the signals in a certain direction. To obtain a high beamforming gain, transmit and receive beam directions should be well aligned with each other. When the MS is in the connected state, the index of the best transmit beam of the BS is fed back from the MS to the BS periodically using the uplink control channels, and the best transmit beam of the MS can be reported through the downlink control channels so that the data can be transmitted using the best beam pair in downlink and uplink.

The candidate frequency bands appropriate for 5G mmWave communications would be around 30 and 60 GHz. Since the free-space path loss and oxygen absorption at the 60 GHz band is larger than at the 30 GHz band, the signal attenuation at 60 GHz is larger than at 30 GHz. Hence, 60 GHz may be more appropriate for mmWave indoor communications in which line of sight (LOS) or short distance transmission are dominant, while 30 GHz may be more suitable for mmWave outdoor communications in which non-LOS (NLOS) or relatively long distance transmission should be supported.

Random Access in MmWave Cellular Networks: Omnidirectional Antenna vs. Directional Antenna

There are some cases in which the best direction cannot be previously known at either the BS or the MS. Those cases are as follows:
- When the MS tries to access the network initially
- When the MS recovers from a radio link failure (RLF)
- When the MS performs a handover procedure

There is a single MS that transmits the preambles during one RACH frame. The power delay profiles (PDPs) for multiple received signals are summed. The signature is then detected by searching the peak in the summed PDP and comparing with the predetermined threshold.

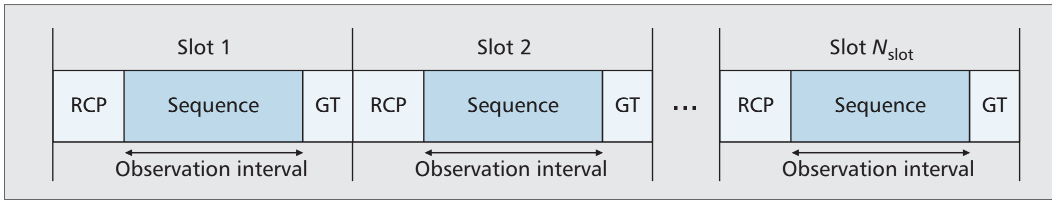

Figure 2. The frame structure for random access in mmWave beamforming cellular networks.

In these cases, the random access procedure is commonly performed between the MS and the BS. Since the best beam pair is not known, the MS has no choice but to transmit the RACH preambles in multiple directions; thus, only a few of those transmissions can achieve a high beamforming gain when the transmit and receive beams are almost aligned. With this in mind, one might ask whether beamforming is still useful although transmit and receive beams are not well aligned yet. In this section, we try to answer that question in part by comparing RACH performance between two cases with and without beamforming, and analyzing the reasons for performance difference.

An exemplary frame structure for the random access preamble transmission (i.e., the first step) is shown in Fig. 2. We simply extend the legacy RACH frame for a single preamble to the case of multiple preambles. The RACH frame consists of consecutive N_{slot} RACH slots. Each RACH slot consists of the RACH cyclic prefix (RCP), the preamble sequence, and the guard time (GT) [6]. For example, if there are $N_{slot} = M_{BS} \times M_{MS}$ RACH slots in a RACH frame where M_{BS} is the number of receive beams at the BS and M_{MS} is the number of transmit beams at the MS, the following procedure can be performed. When the first transmit beam of the MS is used for M_{BS} preamble transmissions, the BS can receive the signals using M_{BS} different receive beams. This is repeated M_{MS} times by changing the transmit beam of the MS. Using all the received signals, preamble sequence detection is performed at the BS.

Evaluation Methodology

There are two important performance metrics that are commonly used to evaluate the performance of RACH: the false alarm probability and the miss detection probability. The false alarm probability is the probability that a preamble sequence is detected when the preamble signatures are not transmitted from the MS during the corresponding RACH frame in Fig. 2. The miss detection probability is the probability that a preamble sequence is not detected when the preamble signature is transmitted in each RACH slot in the corresponding RACH frame. We evaluate the performance of RACH in terms of the miss detection probability when the false alarm probability is set to 0.1 percent. To analyze the effects of beam steering at the transmitter and the receiver, the IMT-Advanced channel model, which is a geometry-based stochastic model, is adopted [7]. The NLOS channel condition is assumed in the urban microcellular (UMi) environment. The mobile velocity is set to 3 km/h. The cell is divided into three sectors, and a BS covers one sector. Uniform linear arrays are used at both the transmitter and the receiver. There is a single MS that transmits the preambles during one RACH frame. The power delay profiles (PDPs) for multiple received signals are summed. The signature is then detected by searching the peak in the summed PDP and comparing with the predetermined threshold.

Comparison of RACH Performance

A single digital chain is used at the BS and MS, respectively. The miss detection probability is plotted vs. signal-to-noise ratio (SNR) with different numbers of antenna elements and different numbers of beams. The number of RACH slots in a RACH frame is $N_{slot} = 16$. Within the RACH frame, the whole transmit-receive beam sweeping is repeated $N_{slot}/(M_{MS}M_{BS})$ times for fair comparison; that is, the total random access duration is the same for each case. In Fig. 3, it is seen that increasing the number of antenna elements at either the transmitter or receiver provides a large performance gain compared to the case of an omnidirectional antenna (i.e., $N_{MS} = N_{BS} = 1$). We can conclude that a performance gain of the directional antenna over the omnidirectional antenna can still be achieved even if a preamble is not always transmitted and received with the best beam pair.

Array and Diversity Gains with Beamforming in Multiple Directions

The performance gains of beamforming in multiple directions compared to the omnidirectional antenna are twofold: the *array gain* and the *diversity gain*. In this subsection, it is assumed that the number of antenna elements at the BS is equal to one (i.e., $N_{BS} = 1$) without loss of generality. In the case of independent fading channels of antenna elements, there is no array gain of multiple transmit antenna elements over a single transmit antenna element (i.e., $N_{MS} = 1$). On the other hand, if the fading is fully correlated (i.e., the correlation matrix of the channel is the rank-one matrix), the average received SNR will ideally be N_{MS} times larger than the independent fading case. Since the antenna elements will be closely spaced in mmWave communications, there will be some array gain for partially correlated channels. In addition, the multiple preambles are transmitted in different directions during a RACH frame, thereby providing multiple signal branches at the receiver. Thus, the diversity gain can be achieved. Therefore, one can still obtain both the array gain and diversity gain from beamforming even if the preamble transmissions are performed in multiple directions. Similarly, in [8], it was observed that the array and diversity gains can be obtained when the MS receives the signals from multiple BSs using beamforming in a cellular network, although the article is not specifically related to random access.

Critical Issues in Random Access in Mmwave Cellular Networks

As shown in the previous section, it is better to use the beamforming technique for random access preamble transmissions using directional antennas. Based on this observation, a random access procedure in mmWave cellular networks is illustrated in Fig. 4. In the first step, preambles are transmitted repeatedly in multiple directions at the MS and received in multiple directions at the BS. The information about the best transmit beam index at the BS should also be conveyed in this step so that the best transmit beam can be used at the BS in the next step. The RAR is transmitted from the BS using the best transmit beam and received at the MS using the best receive beam in the second step. Similarly, the third and fourth steps are performed using the best transmit-receive beam pair.

This naïve approach for preamble transmission in the first step may cause a problem. A high beamforming gain can be achieved only for a few of all transmit and receive beam pairs. Most preamble transmissions cannot obtain a high beamforming gain due to the misalignment of transmit and receive beam directions. Therefore, the preamble duration for RACH should be much longer than that of other uplink control and data channels that use the best beam pair in order to achieve target coverage (e.g., a cell radius of a few hundred meters). Considering that the path loss difference between legacy bands under 5 GHz and mmWave bands around 30 GHz may be more than 20 dB in a UMi environment assuming path loss models in [7], the total duration of a RACH frame is expected to be a few tens of milliseconds, which is much longer than 1 ms in LTE. Hence, it will have a great impact on the initial access, RLF recovery, handover, uplink-downlink configuration, and beam scheduling. In the following, we discuss each issue in more detail. It is worth noting that the access method may not be a problem in IEEE 802.11ad because the service range of the protocol is very short, a few tens of meters at most.

Impacts of Long Duration of the Random Access Preamble

We identify the important issues in the mmWave cellular network by scrutinizing the impacts of four different aspects.

Initial Access and RLF Recovery — For initial access (i.e., moving from idle mode to connected mode), the random access procedure is performed. In order to reduce power consumption, an MS should spend as much time as possible in

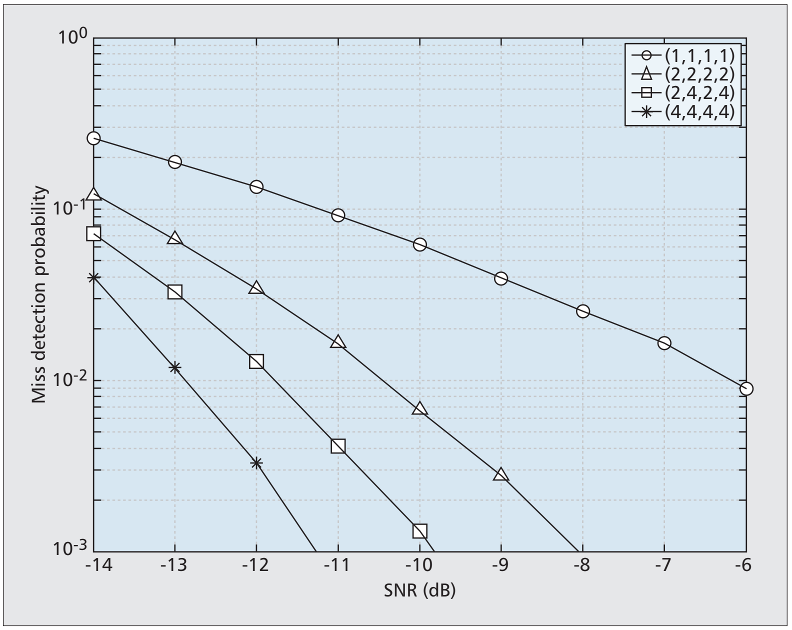

Figure 3. The miss detection probability vs. SNR where N_{slot} = 16. The symbol (N_{MS},N_{BS},M_{MS},M_{BS}) denotes an antenna and beam configuration where N_{MS} and N_{BS} are the numbers of antenna elements at the MS and BS, respectively; and M_{MS} and M_{BS} are the numbers of beams at the MS and BS, respectively.

the idle state. This means that the transition time from idle state to connected state should be short. Due to the long duration of random access, however, it is not easy to design an efficient procedure related to state transition. In addition to the initial access, when the RLF occurs, the MS re-establishes the connection using random access. As the random access duration is long, the service interruption time may also be long, and thus the user experience may be heavily affected.

Handover — There will be a large number of small cells in mmWave cellular networks. As an MS moves across cells, the handover for the MS may occur frequently. Thus, handover time should be very short for guaranteeing the quality of experience (QoE) of MSs in the network. However, because the time required for handover completion may be long due to the random access procedure, the QoE of users may be severely degraded, especially for real-time services such as voice over IP (VoIP). Although a non-contention-based random access procedure can be performed in handover (i.e., a random access preamble signature is assigned by the BS), the fact that the MS should transmit the multiple preambles in multiple directions is the same as the case of the contention-based random access procedure in mmWave cellular networks.

Uplink-Downlink Configuration — In mmWave systems, time-division duplex (TDD) may be more appropriate than frequency-division duplex (FDD) since radio resource efficiency and spectrum flexibility are important in such a wideband system. Due to the long RACH frame, however, many uplink time slots are needed. Hence, it is not flexible to configure the uplink-downlink ratio in the TDD system according to the uplink-downlink traffic ratio.

Beam Scheduling — The number of receive beams that can be simultaneously used in a time slot is limited by the number of receive digital chains at the BS. If the number of receive digital chains is small, the beam scheduling flexibility for data will be low. For example, when there is only one receive digital chain at the BS, it has no choice but to schedule an MS in a time slot where the best receive beam at the BS for the MS is the same as that used for receiving the RACH preamble in the time slot. Moreover, the problem becomes more serious when the uplink data signals for different MSs are multiplexed in the frequency domain rather in the time domain.

POSSIBLE APPROACHES TO ADDRESS THE ISSUES

As mentioned earlier, the main problem of random access is that the total duration of the RACH should be very long since multiple preambles should be transmitted for all transmit and receive beam pairs. To overcome this challenge, we present candidate solutions in the following subsections. One might think that RACH performance would be improved if the preamble bandwidth gets wider. However, we would like to note that RACH performance does not depend much on the preamble bandwidth basically given a preamble duration [6].

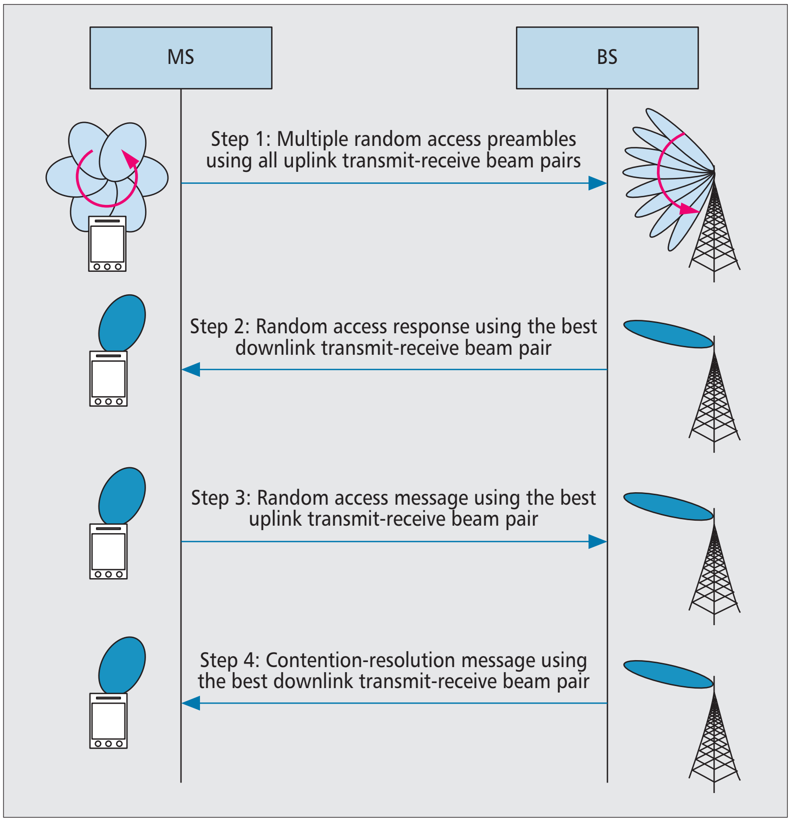

Figure 4. The random access procedure in mmWave beamforming cellular networks.

ENHANCED PREAMBLE DETECTION PERFORMANCE

If we improve the performance of preamble detection, the RACH duration can be reduced for a given cell coverage. The performance depends on the preamble sequence design and the preamble detection algorithm at the receiver. It may not be easy to improve the performance by designing a new preamble sequence since the Zadoff-Chu (ZC) sequence [9] used in LTE already has desired properties such as ideal cyclic autocorrelation and minimum cross-correlation. However, one can improve the performance by enhancing the detection algorithm. For example, the conventional detection algorithm is based on the assumption that the channel response is nearly flat over RACH subcarriers. In practice, however, it is more likely that the MS experiences frequency-selective fading channels. From this point of view, an enhanced detection algorithm was proposed in [10] by taking into account the frequency selectivity of the channel. In mmWave systems, multiple signals are received at the BS; thus, the performance will depend on how those signals are combined. Therefore, a novel combining algorithm needs to be developed to improve RACH performance.

MULTIPLE DIGITAL CHAINS AT THE BS

One possible way to improve RACH performance (i.e., reduce the required SNR) is to use multiple digital chains at the BS. For example, by steering multiple receive beams in the same direction simultaneously, the received signals can be non-coherently accumulated, resulting in performance gain. In Fig. 5, we compare the performance when the number of receive digital chains at the BS is 1, 2, or 4 while the MS still has a single digital chain. It is seen that about 3 dB gain is obtained in terms of the required SNR satisfying the 1 percent miss detection probability when the number of digital chains is doubled. Since the performance will depend on how the multiple beams are steered, it is an interesting issue to determine the directions of multiple receive beams for the RACH.

EXPLOITING BEAM RECIPROCITY

If the mmWave system operates in TDD mode, one can exploit the channel reciprocity for the random access procedure. If the channel reciprocity holds, the random access procedure can be designed so that the MS transmits a preamble in the best direction only and obtains a high beamforming gain. However, the channel reciprocity may not hold due to different characteristics of the RF circuitry of the transmitter and receiver. Fortunately, for the purpose of a RACH, it will suffice to have beam reciprocity; that is, the best transmit-receive beam pair in downlink is the same as the best receive-transmit beam pair in uplink. Therefore, it is important to calibrate RF circuits for ensuring beam reciprocity, especially in NLOS environments.

CELL DEPLOYMENTS

Since the path loss of an LOS channel is much smaller than that of an NLOS channel, one approach to solve the earlier problems is to carefully deploy BSs in locations where an LOS link between BS and MS can easily be formed. In order to cover a large area with this constraint, however, a large number of BSs will be needed. Therefore, the cell planning method becomes more important in mmWave cellular networks.

CONCLUSIONS

An overview of random access in mmWave beamforming cellular networks is presented. We have analyzed the important issues in the design of a random access channel with respect to initial access, handover, uplink-downlink configuration, and scheduling. Through numerical simulations, it is shown that the performance gain from beamforming in multiple directions without knowledge of the best beam pair can still be achieved. As having a large number of antenna elements is not a fundamental solution, we present another approaches and discuss the research challenges. The research on random access for the mmWave cellular network is still at an early stage. We expect that more research on random access will be conducted for successful development of the mmWave cellular network for 5G mobile broadband.

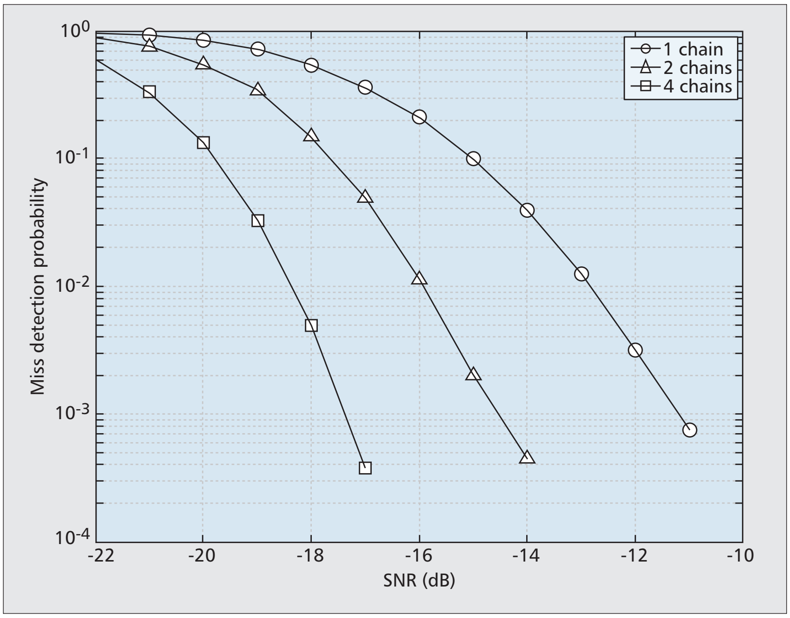

Figure 5. The miss detection probability vs. SNR where $N_{\text{slot}} = 16$. The number of digital chains is 1, 2, or 4.

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