Feasibility of Mobility for 28 GHz millimeter-wave Systems

Based on Outdoor Measurement Campaign
September 2018

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Contents

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Introduction

Due to the large available bandwidth, use of frequencies between 6 and 100 GHz (henceforth called mmWave band) is a key enabler for meeting the target that 5G cellular systems provide user-experienced data rates that are 10 times higher than in 4G and peak rates 20 times higher [1].
Commercialization of 5G mmWave technology will start in 2018 with fixed wireless access (FWA) [2][3], which provides high-speed Internet service to homes where wireline services such as optical fiber cannot be easily deployed. While FWA systems will come first to the market, a lot of recent work on mmWave communications have also concentrated on mobile networks.

For this reason, a lot of recent work on mmWave communications has concentrated on mobile networks [4]. At the same time, standardization of such mobile mmWave systems is actively discussed in 3GPP-NR (Third-Generation Partnership Project-New Radio) [5], the 5G standardization activities of 3GPP.
Incorporating cutting-edge technologies in antenna design and massive-array signal processing [6], the NR mmWave standard is developed for mobility, covering users in LoS (line-of-sight) as well as NLoS (non-LoS), moving at pedestrian or vehicular speeds.
These extended capabilities of mmWave systems will be achieved by using adaptive beamforming, beam-tracking, and fast beam-switching in mobile devices like smartphones. Recent prototype systems prove the possibility of mmWave beam-tracking and handover while users are moving in various environments [7]-[9], especially for high-speed mobility in LoS conditions, and demonstrated high throughput during system operation.
However, there is still a lack of detailed and realistic studies of the feasibility of mmWave mobility support in outdoor cellular networks [4], and there are few experimental investigations of system aspects, such as under what circumstances practical beamforming procedures can track mmWave channel characteristics.
This paper is intended to provide such an investigation, describing the challenges of mmWave mobility support, and providing case studies based on a measurement campaign in an urban environment. We furthermore suggest the system operations required to support such mobility.

Challenges for Mobility of mmWave Communications

Propagation Characteristics of mmWave Frequency with Beamforming

While mmWave communication systems have significant technical benefits, it is also well known that they encounter several challenges arising from radio propagation at mmWave frequencies, including severe free-space path loss, high penetration loss, and diffraction loss.
In urban outdoor environments, high diffraction loss leads to a large percentage of locations that suffer from a stronger shadowing loss compared to the cm-wave band.
This is true also for shadowing by street corners, such that streets with particular orientations can exhibit strong signal attenuation [10].

mmWave systems at least partly overcome these losses by applying directive antennas and/or adaptive beamforming with high gain at both transmitter (TX) and receiver (RX) [6].
Yet, challenges still remain in situations with significant temporal variations of the channel characteristics due to mobility, such as during transition from LoS to NLoS condition. Furthermore, moving objects such as cars, trucks, and people act as random blocking objects, introducing comparatively fast changes of the channel states.
These shadowing variations are faster and deeper at mmWave frequencies because of the sharper shadows thrown by obstacles at higher frequencies.
Due to the sparseness and directionality of the channel, it is essential that significant paths exist into the direction in which the TX and RX form their narrow beams.
In other words, misorientation of the beams due to various factors (user equipment (UE) mobility, random blockers, and changes on channel pathway directions) leads to significant performance loss.
Even in LoS conditions where a beamformed channel has few multipath components (for example, only ground-reflected and direct path), channel quality exhibits strong fluctuation due to small-scale fading [11].

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Critical Issues for Mobility in mmWave Cellular Networks

In this section, we review the mobility support features in cellular networks to better understand the related issues of system performance. We focus on link adaptation including Adaptive Modulation and Coding (AMC), Hybrid Automatic Repeat reQuest (HARQ), and beam-training and tracking in Beam Management (BM).

To optimize system capacity and cellular coverage, the base station (BS) should try to match the data rate to the variations in the received signal quality. AMC operation in link adaptation allows the block error rate (BLER) to be maintained below a predefined target value by adapting the modulation order and coding rate according to the sampled channel quality. In mmWave mobility scenarios, with rapid channel variation on beamformed channels, link adaptation can be critical to retain reliable transmission.

Adaption to the channel is based on feedback of channel state information (CSI) to the TX, where the protocol itself also inevitably leads to latency between the measurement of the channel and the application of the proper transmit power, modulation, and coding rate.

In addition to the AMC operation, HARQ also provides more robustness against fading. HARQ is a combination of Forward Error Correction (FEC) and Automatic Repeat Request (ARQ) that saves information from previous failed decoding attempts for use in future decoding after packet retransmission.
In HARQ with energy accumulation, the signals from different retransmissions are added up with maximum ratio combining to improve the effective signal-to-noise ratio (SNR). For HARQ with incremental redundancy, additional parity check bits are sent during retransmission. The original signal is recovered successfully if the accumulated energy (for energy accumulation) or mutual information (for incremental redundancy) exceeds the required threshold.
However, due to channel variations, if the quality of the received signal is too poor to acquire sufficient energy or mutual information during the allowed retransmissions, the HARQ operation will not be successful. Thus, fast-changing channel variations can introduce another challenge for AMC and HARQ.

For adaptive beamforming, it is usually necessary to use analog beam sets to estimate the angle of departure (AoD) at TX and the angle of arrival (AoA) at RX of the dominant channel components. BS and UE sample the channel subspace adaptively using transmit and receive beam sets within assigned resources. This is done in a case, for example, when the BS sends training beams consecutively in different designated directions and the UE estimates the AoD/AoA by scanning its own beam directions for each BS beam direction and measuring the received power. Then, the BS is fed back the index of the best TX beam and accordingly aligns its transmit beam for data transmission. These beam training operations are known as the beam management procedure. Beam management in mmWave systems usually suffers from the limitations of spectral resources and requirement to frequently repeat the channel subspace sampling, which can be critical in fast-varying fading channels [12]. In contrast, in FWA networks the channel can sometimes be assumed to be quasi-static, so infrequent channel sampling is sufficient.
Note that after the initial access procedure and proper beam alignment, conventional wireless data transmission (including the AMC and HARQ procedures described above) can be performed on the beamformed channel link.

Considering mobile scenarios, such as outdoor pedestrian users carrying mobile devices and vehicular-to-infrastructure (V2I) communication, the BS and the UE should perform periodic beam training within the beam stationarity time duration, such as the time during which the beam-related channel statistics remain the same.
The BS should transmit training beams more frequently to update AoD/AoA estimates since the location of UEs keeps changing. In practical scenarios, the sampled CSI with specific beam pairs might be easily outdated, which might cause beam misalignment and significant performance loss until the beam is recovered.

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Protocol and Conditions supporting the Mobility in mmWave

This section identifies the detailed procedures of the system protocol developed in 3GPP NR [5] for the items reviewed previously, and presents the metric for supporting the mobility in outdoor mmWave cellular networks and the system impact. In cellular networks, such as LTE and NR, the UE can report channel quality indicators (CQIs) to assist the BS in choosing an appropriate modulation and coding scheme (MCS) level for the data transmission.
The UE determines CQI such that it corresponds to the highest MCS, allowing the UE to decode transport blocks with error probability not exceeding 10 %. Due to the inherent latency between the reported measurement of CQI and the actual use of the MCS, and the channel variation during that time, the system relies on the system margin of the BS scheduler to handle the inaccuracy of the CQI report.

The key metric for the feasibility of mobility in AMC operations is whether the connected link is maintained over the latency time of the protocol operation.
Thus, the feasibility of the AMC operation depends on the change rate of the beamformed channel.
We investigate how much the channel power changes for a given latency in the following sections.

If the transmission of a transport block fails, then the RX indicates this with a HARQ NACK (negative acknowledgement). When a NACK is received, or when a certain time elapses without any feedback from the RX, the TX retransmits the transport block. The RX combines the new symbols with the original symbols, and tries to decode the block again. For validating the mobility support in HARQ operations, we investigate below the performance with respect to the amount of loss in fading channels during the transmission and retransmission by comparing the accumulated energy obtained from retransmissions. Then, the residual error of the HARQ process will be derived. To simplify the analysis, we assume that no additional latency from the HARQ timer is introduced awaiting the retransmission.

As a further impact on link adaptation techniques, the mobility of the users also changes the path directions, which necessitates frequent beam-tracking.
However, on each resource, one RSRP (reference signal received power) sample is measured for a specific BPL (beam-pair link) because the beamforming technologies in most mmWave systems limit the transmission to a single beam direction per time unit and radio chain.
The UE reports the information of the N-best BPL index and corresponding RSRP to the BS, which can make the BS to choose a proper TX beam among N-RSRPs of the best beams. Note that the RX beam at the UE side can be changed by measuring RSRPs at every update, while the TX beams can only be changed after the BS is provided with the RSRPs of the TX beams.

For beam management, the system has to sweep, within a certain period, all combinations of BPLs with limited resources. Due to channel variations, the measured samples become outdated even as this process is going on, and the UE and BS thus choose the best BPL among the outdated measurements. In Fig. 1, an example of the beam-tracking based on BPL measurement shows the received power measured while sweeping all combinations of directional beam pairs on TX and RX. This example depicts only the two strongest BPLs from the measurement campaign [11], which will be discussed in detail in the Case Studies section later; it depicts a part of the transition area of LoS to NLoS area (6 m movement), around 60 m in distance index as the UE is moving on the route shown in Fig. 2(a).
It demonstrates that the beamformed channel states vary fast, especially in the transition area where diffraction and shadowing occur. The solid lines represent the instantaneous channel per BPL sampled every 5 ms.
In a practical BM procedure, the instantaneous channel variation on each BPL is not easily observed in the UE operation because of the large spectral resources such sounding would require. Instead, all channels of BPLs are sampled at the yellow points with a sweeping periodicity (whose value is an important system design parameter), and each BPL sample is measured sequentially with the assigned resources. The dotted lines are the perceived channels measured once within the sweeping period (160 ms in this example) by the UE. The fast variations and the longer updating period of the beamformed channel cause the mismatch between the instantaneous channel and the perceived sampled channel.

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As shown in Fig. 1, the current operating TX/RX beams (BPL 2) are selected among the measured BPLs within a full-sweep period until a better channel is measured.

Around 6100 ms in Fig. 1, another beam (BPL 1) is selected based on the measured channel; however, the channel is fading rapidly while the BPL measurement is not updated due to a sweeping period that is slower than the channel change rate. Thus, the BM operation with outdated beam-tracking (green solid line in Fig. 1) induces inefficiency.

The key question for supporting mobile beam-tracking is whether the loss of beam-tracking efficiency is frequent and critical for link robustness. The following section analyzes the BM operation with mobility and the conditions for conducting efficient BM operation.

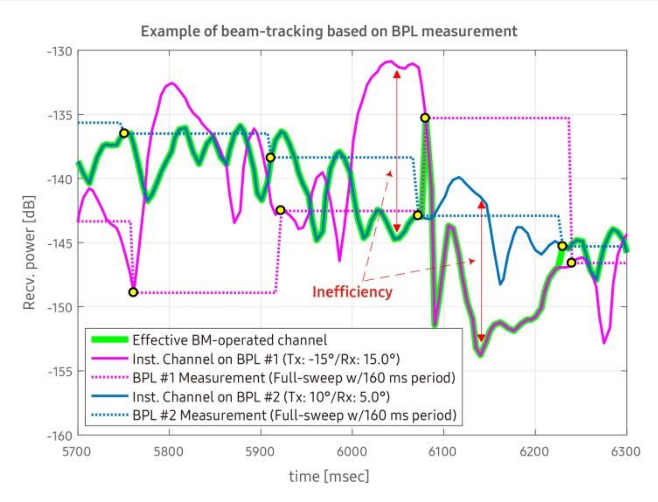

Figure 1. Example of beam-tracking operations with mobility in mmWave wireless systems

Feasibility Analysis of mmWave Mobility

Analysis of Beam-Tracking Feasibility Based on Outdoor mmWave Measurement

The main focus of this section is to provide insights from a mobility measurement campaign concerning the operation of mmWave systems in order to design a robust and efficient beamformed system. Analysis of mmWave beamforming system performance requires accurate measurement of the angular power spectra and their temporal variations.

Recently, some measurement works have been conducted based on the advanced phased-array antenna beamforming [9]. However, most of the directional outdoor measurements for mmWave frequencies were performed with rotating horn antenna channel sounders [14], which are not able to measure in real time and thus are not well suited for analysis of dynamic channels, and/or the acquisition of the large number of spatial samples required for tracking analysis.

Thanks to a new channel sounder operating in the 28 GHz band that is capable of performing directionally resolved channel measurements in real time [13], a mobility measurement campaign was conducted with extensive samples in a typical urban-like environment with moving UE.

The main specifications for the sounder and sounding signal are listed in Table 1, and further details of the sounder and its validation can be found in [13].

The measurements were performed on the campus of the University of Southern California, in Los Angeles, CA, in an area that resembles a typical urban environment, including a LoS-to-NLoS transition area. The case study for mobility feasibility was conducted in a mixed region containing 53 m of LoS route and 40 m of NLoS or transition route, which is marked with a light-blue color arrow line in Fig. 2 (a).

While moving along the route, all channel links (up to 703 combinations of beamformed links with 19 TX beams and 37 RX beams) are measured. One MIMO channel snapshot (for example, all beam pair combinations) is captured in a spatial sampling with an average rate of one sample per 5 cm as we moved the RX slowly.

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A total of 1.6 million measurements of channel impulse responses are logged on the route. These extensive measurements are made feasible by the fact that our sounder can perform fast beam-switching by means of an electronically steered phased array antenna.
Reference [11] discusses further details of this measurement campaign. In post-processing, we emulate fast UE speeds, assuming that the UE moves with a constant speed of 36 km/h for convenience (similar to typical vehicle moving speed in urban areas). The time index of all channel snapshots is then scaled to emulate this UE moving speed (for example, 1 cm movement in 1 ms).

To analyze the characteristics of each beamformed channel link, the received power per BPL is represented in Fig. 2 (b). Out of a total of 703 BPLs, 11 BPLs are plotted, where each selected BPL is the best at least once along the route. In LoS conditions, which occur up to a time index of 5000 ms, the interactions of the direct path and ground-reflected path [11] introduce the fluctuations of the received signal power and require properly designed link-adaptation algorithms.
After turning onto the NLoS route, which occurs at the 5200 ms time index, the received signal power in Fig. 2 (b) rapidly decays up to 50 dB due to blocking from buildings and foliage around the corner.
At the transition from LoS to NLoS, the BM needs to change the connected BPL and to track the channel changes. By utilizing the angular diversity in the NLoS region of the measurement campaign, more than 15 dB gain can be achieved when the UE adaptively changes the beam from the BS direction toward the street-corner direction (for example, from light-blue line to green line in the 7000-9000 ms time index range in Fig. 2 (b)). As a further observation, it is also interesting how the beam directions of the channel changes in a mobility scenario, which is shown in Fig. 2 (c). In the LoS part, the *order* of the received power of BPL is stable, and little changes in the best beam direction at both TX and RX occur. In the transition area, around time index 7000 ms, the best beam direction on the RX side changes quickly because many reflected paths are generated in the transition area. However, the best direction of the TX beam remains stable even in the NLoS part. It is observed that the best receiving beam changes occur 130 times while the best transmitting beam changes are counted only 60 times on the whole moving route.

Case Study I: Channel Quality Change-rate per BPL

Feasibility of AMC Protocol

To check the feasibility of the AMC operation in mmWave mobile systems, we first investigated how much the channel power changes and fades during the AMC operation latency.

Table 1. Key Features of mmWave Channel Sounder

Hardware Aspects	
Center Frequency	27.85 GHz
Instantaneous Bandwidth	400 MHz
Antenna array size	8 by 2 (for both TX and RX)
Horizontal beam steering	-45 to 45 degrees
Horizontal 3 dB beam width	12 degrees
Horizontal steering steps	5 degrees
Beam switching speed	2 us
TX EIRP	57 dBm
RX noise figure	< 5 dB
ADC/AWG resolution	10/15-bit
Data streaming speed	700 MBps
Sounding Waveform	
Waveform duration	2 us
Repetition per beam pair	10
Number of tones	801
Tone spacing	500 kHz
PAPR	0.4 dB
Total sweep time	14.44 ms
MIMO repetition rate	5 Hz

From the received channel power per BPL in Fig. 2 (b), the power loss is defined as the difference between the received channel power measured from the downlink reference signals and the prevailing channel condition of the downlink data transmission, for example the amount of inaccuracy of the CQI report, given the operation latency.

In the analysis, it is assumed that the AMC operation can be initiated at any data sample used for CQI report, and all samples are used for the analysis. For simplicity of analysis, we use the power-loss metric instead of BLER, and perfect feedback of CQI reports from UEs to BS is assumed.

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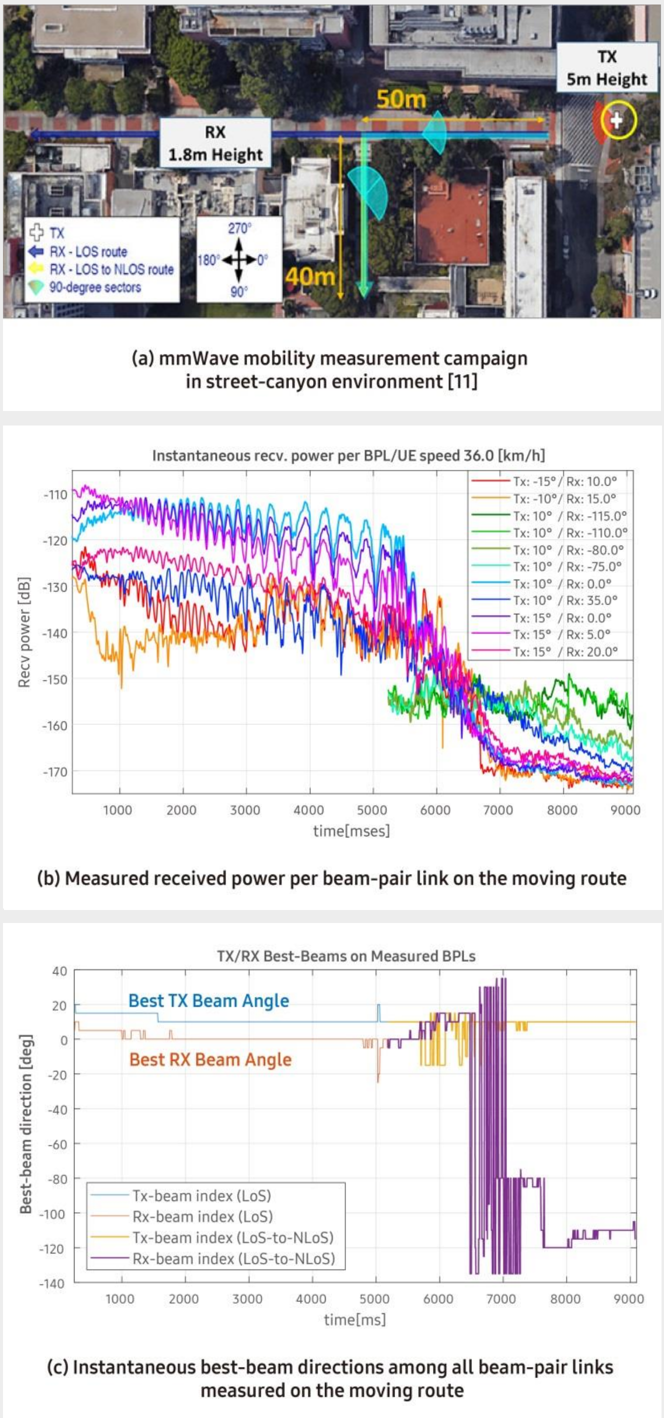
For acquiring more data for statistical information, all 11 best BPL channel powers are collected.



(a) mmWave mobility measurement campaign in street-canyon environment [11]

(b) Measured received power per beam-pair link on the moving route

(c) Instantaneous best-beam directions among all beam-pair links measured on the moving route

Figure 2. Environment of measurement campaign

In Fig. 3 (a), the CDF (cumulative distribution function) of the power loss for different protocol latencies is represented.

Considering a system based on the 3GPP NR profile, the AMC latency is set to around 4 slots, which is the delay between the UE measurement of the downlink RS and the report of CQIs. Further latency-increasing protocol aspects, including the scheduling process, are assumed to contribute another 4 slots. With 0.25 ms duration of a slot for the case of 60 kHz sub-carrier spacing in the mmWave profile, the total latency from the channel measurement to the actual downlink data transmission is typically up to 2 ms. Adding the periodicity of CQI reports as 10 ms, the maximum latency of AMC protocol would be 12 ms. In Fig. 3 (a), a 1.5 dB power loss is observed on the measurement of downlink reference signals for the 15 ms protocol latency case. It is also observed that even 50 ms operation latency only introduces less than 3 dB power loss on channel measurements. By increasing the UE speed beyond 36 km/h, the operation latency can be properly scaled.
For example, the power loss for 15 ms protocol latency around 100 km/h can be estimated as 3 dB in the simple analysis.
In the previous section, it was discussed that the system margin is usually considered for stable AMC operation. Based on the measurements, it is expected that a mmWave cellular system with mobility requires less than a few dB system margin for operating the AMC protocol properly in a typical urban scenario, and this amount of system margin in AMC operation is feasible for system implementation.

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Feasibility of HARQ Protocol

Even with stable AMC operation, transmission errors are unavoidable and these fails (for example, samples over the 90th percentile of power loss) are handled by the HARQ retransmission protocol. We investigate how much error is inevitable while retransmission gains are added, and then whether the residual error after retransmission is large enough to create a failure of connection in an mmWave mobility scenario. For performance evaluations of system-level operation, a simple model is used to check the feasibility of HARQ. We use the power loss during the duration from the channel measurement (for CQI report) to the retransmission for the samples that failed to be decoded in the original transmission.

We consider that the retransmission operation includes the latency of HARQ feedback and scheduling, where we assume that additional 8 slots for HARQ round-trip time, for example 2 ms latency, as in the section on Feasibility of AMC, is required. For the case of 50 ms AMC latency operating with 3 dB margin in each MCS level, from Fig. 3(a), 10 % of the samples fail.

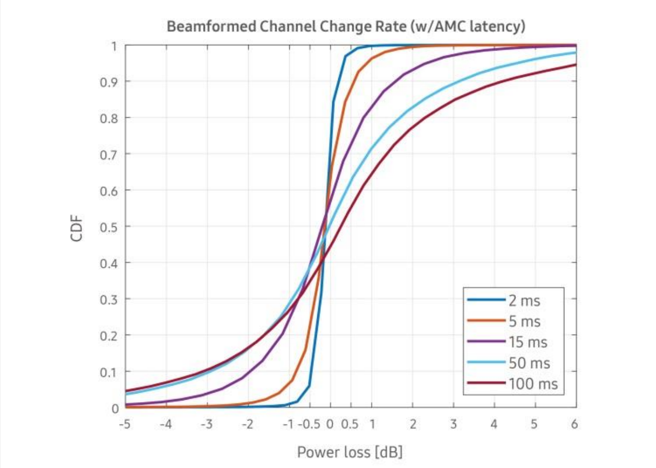
The failed samples of the AMC operation undergo retransmission with HARQ procedures within additional latency, then the samples that have more power loss than retransmission gain are treated as fails after the first retransmission.
In Fig. 3 (b), the CDFs of the power loss for the retransmission cases are plotted, which compensate the system margin from the original transmission.

The accumulated energy is doubled for the first retransmission, and the gain is simply derived as 3 dB in the analysis.
For the case of 50 ms latency case in AMC operation, there is roughly 1.8 % residual error after the first retransmission (for example, 10 % failure of the original transmission times with 18 % error on the retransmission).

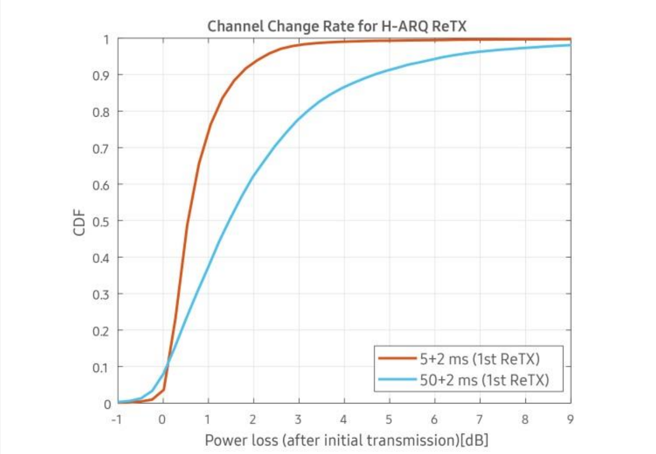
Similarly, if the power losses of 5 ms latency are compensated by 0.5 dB margin, 98 % of samples are successful for retransmission, and it has 0.2 % residual error after the first transmission.
From these observations, the HARQ operation will be feasible with less than 1 % residual error for the shorter latency cases, for example less than 10 ms latency.

Case Study II: Beam Change-rate

Inherently, practical beam-tracking operations induce a delay on updating the channel per BPL because each BPL is only updated once during the measurement period. The measured BPL is easily outdated in fast-varying channel environments, and it introduces beam mismatches in BM, as shown in Fig. 1.



(a) CDF of BPL's power-change rate for AMC



(b) CDF of retransmitted BPL's power-change rate for HARQ

Figure 3. CDF of channel power change rate on beam-pair links

For analyzing the beam-tracking operation, the performance metric is defined as inefficiency of beam-tracking caused from beam misalignment, which is the difference between the genie-aided beam-tracked channel with the instantaneous

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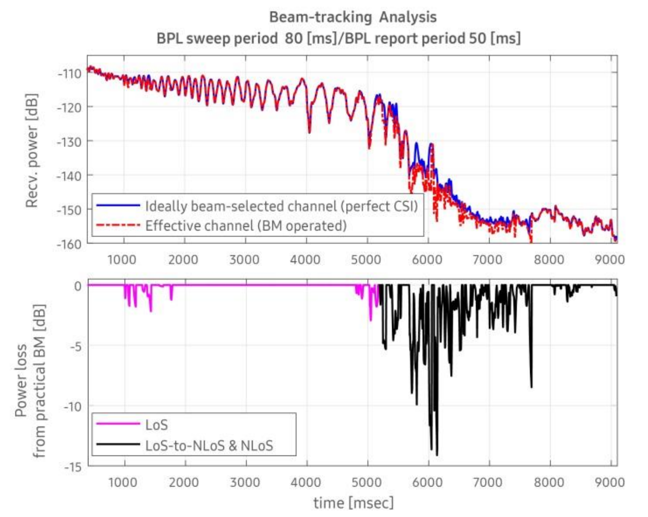
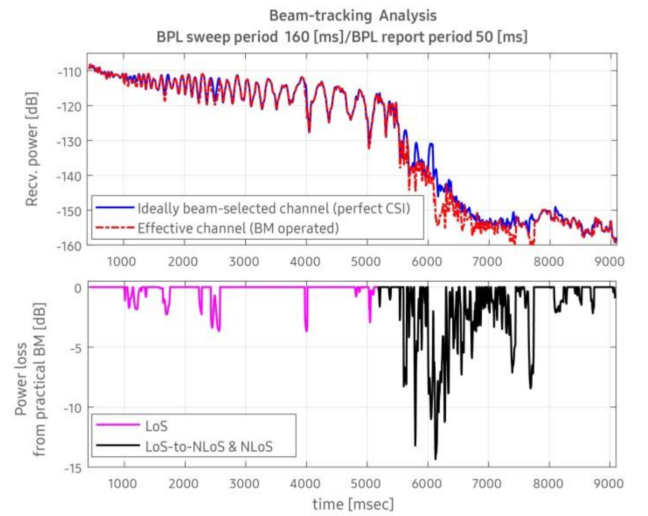
measurement and the practically beam-tracked channel based on the RSRP measurement.

Note that the previous example case in Fig. 1 was analyzed only in the LoS-to-NLoS transition region. We now show the general analysis on BM over the complete route including LoS, NLoS, and transition area. In Fig. 4, the beamformed channel received power for two beam-sweeping periods and the power loss from BM inefficiency are presented.



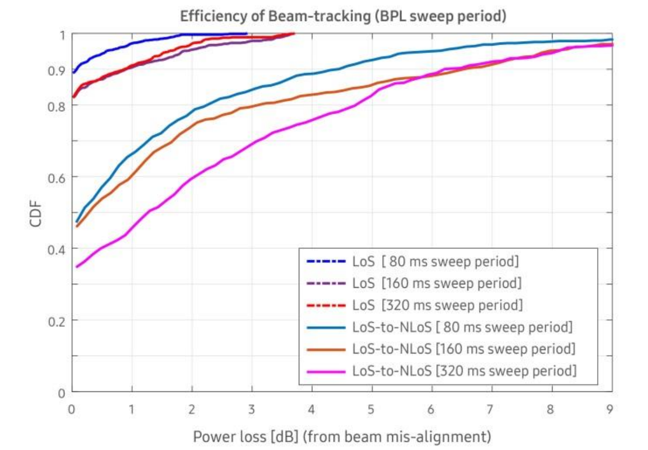
(a) Beam-sweeping period 80 ms



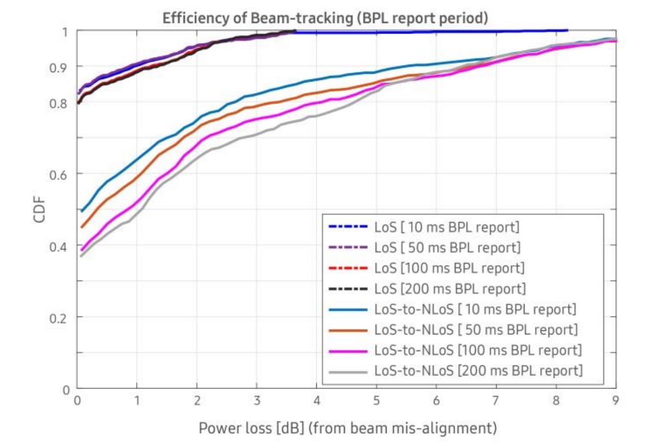
(b) Beam-sweeping period 160 ms

Figure 4. Performance analysis of beam-tracking along the moving route

Similar to the observations of the previous section, the LoS region is well matched between the genie-aided beamforming case and effective beamforming case because no frequent beam changes occur in a short period. Overall, due to constraints on the BM operation, the practical beam tracking cannot be perfect due to various latency factors. In the analysis, all TX beams are swept every 10 ms (synchronization signal-block periodicity from the NR profile), and the UE changes all RX beams for each TX sweep to measure all combinations of TX and RX beams.



(a) CDF of beam management power-loss on BPL sweep period



(b) CDF of beam management power-loss on BPL report period

Figure 5. Analysis of beam-tracking mismatches in beam-management

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The number of RX beams emulated in Fig. 4 is 8 for an 80 ms sweep period and 16 for a 160 ms sweep period. As expected, it is observed that longer sweep periods have more frequent, and longer duration of, misalignments.

The performance and efficiency of the beam-tracking operation are related to three latencies, namely beam-sweep period, BPL-updating period (for example, UE updates the best BPL index to BS), and BPL time-filtering. We investigated the performance loss statistically and evaluated the effect of these latencies by changing the sweep period and the updating report period in Fig. 5. In LoS conditions, the loss from beam misalignment is less than 1 dB in the 90th percentile.
More loss can be expected in NLoS conditions, and longer latency causes larger power loss in NLoS cases. From the analysis, the sweeping period has more impact on BM operations. In order to maximize efficiency, all factors should be taken into account. Considering the practical mmWave mobility support, including severe NLoS cases, accounting for additional loss in system design for mmWave cellular networks is recommended. As an example analysis on the measurement, the additional loss can be up to 6 dB in NLoS and up to 1 dB in LoS, which can occur with 10 % probability of all samples on the measurement campaign.

Insights on mmWave System Design

The following conclusions can be drawn for mmWave systems with mobility when operating according to a 5G NR-like protocol:

- Supporting AMC operation properly requires less than a few dB system margin in a typical urban mobile scenario.
- The HARQ protocol will be operable with less than 1 % residual error for the shorter latency cases (less than 10 ms latency).
- From the observations of the measurement campaign, the changes of best-beam direction at the UE are much more frequent, and it is preferable to design UE antenna arrays with wide angular reception.
  The trade-off between the beamforming gain and the full-sweep periodicity (for example, related to the number of beams to be swept) for efficient beam-tracking without beam-mistracking loss deserves further study.
- When frequent changes of the BLPs occur, a pool of alternative beams to be switched should be provided by the BM algorithm. Utilizing angular diversity provides significant gains, in particular in NLoS condition; this can be implemented, for example, by sub-array diversity [15].
- More beam-mistracking loss can be expected in NLoS conditions, and longer latency causes larger power loss in NLoS cases. In practical mmWave BM procedure design, accounting for up to a few dB in NLoS is recommended for covering up the most environment (i.e. in the 90th percentile).

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Conclusion & Future Work

Despite recent advances in mmWave communications systems, many technical challenges have to be solved to launch initial commercial 5G services from 2018.
In particular, significant efforts are ongoing in 3GPP to prepare mmWave cellular networks for user mobility. This paper summarized the critical issues for supporting mobility, namely fast beam-tracking and fast link-adaptation. It also provides some insights, based on the results of a measurement campaign, that supporting mmWave mobility is feasible for typical vehicular speeds in an urban environment when employing the 5G NR system settings.
Some remaining issues, which are not treated in this paper, include analysis of handover procedure in mmWave networks, UE-rotation effect, and sensitivity analysis of beam width at the mobile user level.

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Abbreviations

AMC	Adaptive Modulation and Coding
AoD	Angle of Departure
AoA	Angle of Arrival
BS	Base Station
BM	Beam Management
BPL	Beam-pair Link
BLER	Block Error Rate
CSI	Channel State Information
CQI	Channel Quality Indicator
CDF	Cumulative Distribution Function
FWA	Fixed Wireless Access
FEC	Forward Error Correction
HARQ	Hybrid Automatic Repeat request
LoS	Line-of-Sight
MCS	Modulation and Coding Scheme
NACK	Negative Acknowledgement
NR	New Radio
NLoS	Non-Line-of-Sight
RX	Receiver
RSRP	Reference Signal Received Power
SNR	Signal-to-Noise Ratio
TX	Transmitter
UE	User Equipment

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