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Blockage robust millimeter-wave networks†

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Millimeter-wave (mmWave) technique (from around 24 GHz to 300 GHz) becomes a key enabler of high date rates for future mobile communications [1]. In spite of many appealing benefits, mmWave communications also encounter several critical challenges, i.e., very weak capability in penetration, diffraction and high-order reflections, due to the short wavelength [2]. That indicates, the transmission in mmWave bands can be blocked easily if any obstacle, e.g., human body or vehicle in motion, occurs on the propagation path. From the reliable communications perspective, the blockage seriously deteriorates the robustness performance of mmWave communications, e.g., 20–30 dB loss in terms of power for human-induced blockages [2]. Thus, for delay-sensitive real-time applications based on mmWave networks, preserving the connectivity in the presence of blockages is a very crucial task. In this paper, we comprehensively review the research achievements on the robustness of mmWave networks.

Anti-blockage strategy: beam switching. The key idea to combat the blockage of mmWave links is to perform beam switching. There are two main roadmaps for beam switching: one is via relays, and the other is via reflectors. By adjusting beam orientation adaptively, namely, beam switching, both the source and destination search the available alternative from the surroundings to reconstruct the wireless link, when encountering unexpected blockages. The candidate path can be provided by either the relay(s) or the first-order reflector(s).

• Beam switching via reflectors. Clearly, mmWave signal from first-order reflector suffer more degradation in terms of power, i.e., roughly by 10–30 dB [3], relative to that from the light-of-sight (LOS) path. It is known that, the loss of signal strength via reflections heavily relies on the permittivity of reflective material and the incident angle. Thus, the mmWave signal over the reflection path sees different attenuation in various environments.

For outdoor scenarios, there are fewer objects that can effectively act as first-order reflectors, and the commonest contributor is the ground. It is reported in [4] that, reflected signals may experience a loss ranging from 10 to 34 dB, which makes it challenging to preserve the link via the ground reflection. Unlike outdoor cases, there are abundant reflectors in the indoor environment, e.g., wall, floor, window, and ceiling, and the resulting loss by indoor reflectors is also relatively smaller. The feasibility of data transmissions via reflectors in indoor scenarios has been extensively studied. Thus, the scheme of beam switching via reflectors is more suitable for indoor mmWave applications.

• Beam switching via relays. Relaying is an alternative way to circumvent obstacles. Signals received at the relay are processed and forwarded

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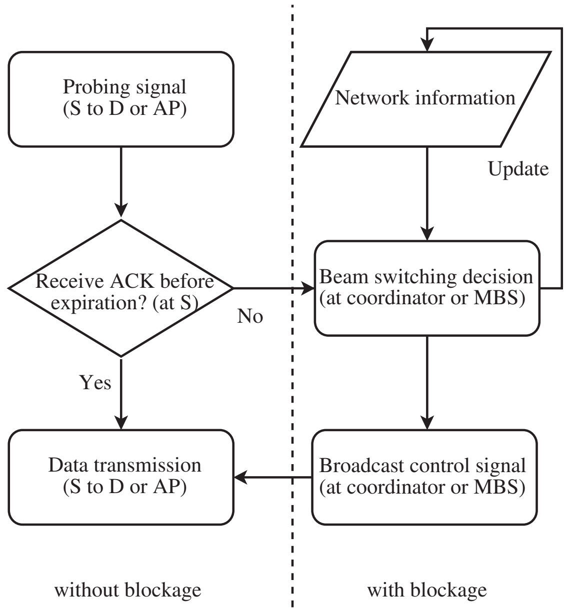

Figure 1 Flowchart of beam switching protocol for indoor or outdoor scenarios.

at the expense of additional power (compared to the method via reflectors), and hence the signal-to-noise ratio (SNR) at the destination can still be somewhat guaranteed.

Due to the use of highly directional antennas in mmWave networks, the problem regarding the optimal beam switching via relays, e.g., maximizing the end-to-end throughput in the presence of random link blockages, usually can be reduced to a matching or coloring problem for the relay-selection scenario, or a routing problem for the multi-hop scenario. It is known that, relay placement largely affects link robustness. In [5], the problem of robust relay placement in 60 GHz WPANs with directional antenna is investigated, where the robust minimum relay placement problem (aiming at minimizing the number of relays for deployment) and the robust maximum utility relay placement problem (aiming at maximizing the network utility) are formulated and analyzed, respectively. In the recent work [6], a multi-hop relaying transmission scheme is developed for mmWave communications with directional transmissions, where blocked flows are steered around obstacles via establishing multi-hop relay paths.

• Hybrid beam switching scheme. Clearly, above two schemes have respect strengths, e.g., in terms of power consumption or scenario applicability. Thus, a hybrid beam switching scheme, i.e., either scheme can be selected for beam switching dynamically, is promising if both relay(s) and reflector(s) coexist. In [3], an adaptive routing algorithm with respect to hybrid scheme is proposed to combat random blockages for indoor mmWave networks, where proper reflector(s) or relay(s) can be dynamically selected for the least signal attenuation, such that the optimal throughput and outage performance can be achieved.

Protocols for beam switching. Among the existing standards on mmWave communications, the application of dynamic time division multiple access (TDMA) is a prevailing technique proposed for medium access control (MAC). By TDMA-based MAC, when encountering random blockages, the protocol for maintaining link connectivity during data transmissions mainly consists of two phases, i.e., blockage detection and beam switching. The flowchart of beam switching for indoor or outdoor scenarios is illustrated in Figure 1.

For indoor scenario, most of mmWave applications emerge in a homogeneous manner, i.e., devices in the network are with similar configuration, radio access technology, and communication protocol. In this case, to fulfill the beam switching, an efficient way is to use the centralized coordinator or controller, which responds for beam synchronization and management. As shown in Figure 1, the centralized coordinator participates in beam switching when encountering blockages. The prerequisite for is that, the centralized coordinator needs to maintain and update the channel gain matrix and routing table, dynamically [3, 7].

Due to the limited coverage of mmWave communications, mmWave networks for outdoor applications need to cooperate with other systems in other frequency bands, e.g., 4G LTE and/or WiFi, thereby establishing the heterogeneous architecture. A heterogeneous mmWave network architecture potentially consists of mmWave access points (APs) and macro-cell base stations (MBSs), operating at lower frequency bands, i.e., sub-6 GHz. The MBS mainly takes care of network signaling, such as cell discovery, scheduling and controlling, which ensures the full coverage and reliable connections between user devices and AP(s). The anti-blockage procedure is perform according to the protocol in Figure 1, where MBS participates in beam switching. Another promising scheme in practical is the backup-connectivity design, where multiple candidate connections are established as backups. Those candidates may be operated in different bands, and the optimal candidate will be activated immediately for resuming the data transmission, as long as the primary path is unavailable due to blockage. Related efforts can be found in the recent work [8].

Conclusion. This article investigated the robustness issue in mmWave networks, where existing achievements regarding basic anti-blockage techniques and protocols for different scenarios with random blockages were comprehensively reviewed.

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