# On the Benefits of Multi-hop Communication for Indoor 60 GHz Wireless Networks

Chanaka Samarathunga*, Mohamed Abouelseoud†, Kazuyuki Sakoda‡, Morteza Hashemi*
*Department of Electrical Engineering and Computer Science, University of Kansas
†Sony R&D Center US, San Jose lab, ‡Sony R&D Center Japan, Tokyo lab

***Abstract*—The spectrum-rich millimeter wave (mmWave) frequencies have the potential to alleviate the spectrum crunch that the wireless and cellular operators are already experiencing. However, compared with traditional wireless communication in the sub-6 GHz bands, due to small wavelengths most objects such as human body, cause significant additional path losses (up to 20 dB), which can entirely break the mmWave link. Also, mmwave links suffer from limited range of communication. In this paper, we resort to network layer solutions to demonstrate the benefits of multi-hop routing in mitigating the blockage issue and extending communication range in mmWave band. To this end, we develop a hop-by-hop multi-path routing protocol that finds one primary and one backup next-hop per destination in order to guarantee reliable and robust communication under extreme stress conditions. System-level simulations based on the IEEE 802.11ad specifications demonstrate that the proposed routing protocol provides a reliable end-to-end throughput performance, while satisfying the latency requirements.**

## I. Introduction

Due to the emerging applications and the need for higher capacity, current sub-6 GHz wireless spectrum is not enough to cope with the recent demands for high data rate applications ranging from augmented/virtual reality to wireless HD video streaming. Millimeter wave (mmWave) bands – between 30 GHz to 300 GHz – have been contemplated as a solution to mitigate the existing spectrum scarcity in the sub-6 GHz. However, enabling mmWave wireless systems in general requires properly dealing with the channel impairments and propagation characteristics of the high frequency bands. In particular, due to the high propagation losses, mmWave provides a limited range of communications. Also, high penetration, reflection and diffraction losses reduce the available diversity and limit non-line-of-sight (NLOS) communications. Due to the small wavelength of mmWave, most objects in the propagation environment lead to blocking and reflection as opposed to scattering and diffraction as in the sub-6 GHz bands. The measurement results in [1] suggest human body can increase the path loss by more than 20 dB.

Currently, there is arguably an adequate understanding of physical layer issues and signal characterization [2, 3] as well as MAC layer designs for mmWave systems [4]. By contrast, the upper layers of the protocol stack are still largely unexplored and the existing protocols are not tailored for the mmWave bands. Multi-hop networking can be a viable solution to mitigate the issue of limited range of communications as well as the sensitivity to blockage. Notwithstanding the benefits, multi-hop communication adds additional overhead by requiring exchange of metadata (e.g., route discovery messages), which is more challenging due to directional communication in mmWave bands. In addition, it is not clear that multi-hop networking satisfies the latency requirements due to extra processing, queuing, and channel access latency at relay nodes. For instance, the IEEE 802.11ay use-case document specifies the latency and jitter requirements of less than 5ms for 8K UHD wireless transfer at smart homes as well as for augmented reality/virtual reality headsets and other high-end wearable devices [5].

There are several works proposing directional MAC protocols for multi-hop wireless networks [6–9]. The authors in [6] have proposed slotted ALOHA-based protocol for ad-hoc networks with devices using adaptive array smart antennas, and [7] has proposed polling based MAC protocol in order to discover and track its neighbors. While these protocols are designed for directional systems, they are not tailored for mmWave and do not address frequent route break scenarios that happen more frequently in mmWave bands compared to sub-6 GHz frequencies.

To mitigate the blockage issues in mmWave systems, there are several physical and MAC layer proposals such as exploiting reflection paths from walls [10], using intelligent reflecting surfaces [11] and integrating mmWave with lower frequencies [12, 13]. There are also some works proposing deflection routing schemes for throughput improvement and mitigating blockage issues [14]. The source device finds a relay and creates a deflection route when there is a blockage in direct path [14]. In this method, an alternating route is found when they detect a blockage. However, it is essential to have a back-up route identified and ready to be deployed even before the blockage happens. In this case, real-time communication can quickly be resorted when the blockage actually occurs.

In this paper, we investigate the performance of multi-hop mmWave communication for indoor 60 GHz applications and demonstrate the benefits of multi-hop routing protocols for blockage-prone and range-limited mmWave links. Due to the nature of use-cases for indoor mmWave systems (e.g., real-time high data rate applications), a blocked link should quickly be detected and replaced by an alternative link. As such, we propose a hop-by-hop multi-path routing protocol that is efficient and fast in switching to a *reserved ready-to-use link* towards the destination. We implement the proposed protocol on top of the 802.11ad PHY and MAC specification, and investigate its performance under different scenarios. In summary, the contributions of this paper are twofold: (i) we develop and implement a hop-by-hop multi-path routing protocol that is tailored for mmWave systems, and (ii) through extensive system-level simulations, we investigate the performance of multi-hop communication for indoor mmWave systems in terms of satisfying the throughput and latency requirements.

## II. Hop-by-Hop Multi-Path Routing

We consider a mmWave network that consists of several STAs such that the intermediate STAs are able to relay data traffic from the originating STA to the destination STA (depending on the connectivity and links configurations between STAs). Each directional link is associated with a cost metric that captures the quality of that link. Cost of a route is defined as the summation over the cost of individual constituent links of the route. The goal is to find one primary and one backup link from the originating STA to neighbor STAs to achieve a *hop-by-hop multi-path routing*. In hop-by-hop multi-path routing, the routing table at each STA contains two next-hops per destination (not for the entire route). If the link to the primary next-hop is blocked, the STA switches to its backup next-hop. In [15], hop-by-hop routing is proposed for the Internet data packets that can be split between multiple next hop switches. This in turn improves the efficiency and robustness. In this paper, hop-by-hop routing is considered for mmWave systems in order to mitigate blockage issues. In traditional multi-path AODV protocols (e.g., [16]), when the primary path from the source to destination is unavailable, the source node switches to the *next alternate end-to-end path*. In contrast, the hop-by-hop multi-path routing adds a local repair capability to each node (source and intermediate) by switching to an alternative link for the blocked link, without the need for an entire route change by the source. This may result in a transient non-optimal end-to-end route, which can be fixed in the next round of routing tables reset.

**Route Discovery Messages:** In order to disseminate the routing control messages across the network, either omni-directional transmissions or directional signals can be used. In the former, due to the short-range nature of mmWave signals, omni-directional signaling may not reach to the neighbor nodes. In this paper, we assume that the STAs have performed the sector sweep (SSW) procedure with the 1-hop neighbors. In order to establish a multi-hop route, the originating STA sends directional RREQ frames to its neighbor STAs. Each 1-hop neighbor receives the RREQ frame and updates its reverse route to the originating STA. Each neighbor STA then forwards the RREQ to its 1-hop neighbor as well, excluding the transmitter STA from which the RREQ was received. As the forwarding continues, intermediate STAs may receive duplicate RREQ from other STAs.

By receiving RREQ messages, the best RREQ and second best RREQ frames (in terms of cost) determine the next-hop and backup next-hop node to the originating STA in the routing table of the intermediate STAs. In order to reduce the routing overhead, the intermediate STA picks the best received RREQ, and forwards it to its neighbor STAs. To avoid looping, the STA records the forwarding action in its Forwarding Table.

TABLE I: Simulation parameters

| Simulation Parameter | Value |
|---|---|
| Transmit power | 18dBm |
| Preamble detection threshold | -68dBm |
| Noise level | -70.6dBm |
| Energy detection threshold | -48dBm |
| Channel access scheme | Contention based |
| Beacon interval (BI) | 100ms |
| Beacon header interval (BHI) | 5ms |
| Data transmission interval (DTI) | 95ms |
| Rate controller | ARF |
| Maximum number of aggregated MPDU | 64 |
| Transmit opportunity duration (TXOP) | 300 $\mu$s |
| Human blocker path loss | 20dB |
| Human blocker dimensions (length, width, height) | (0.5m, 0.5m, 1.8m) |

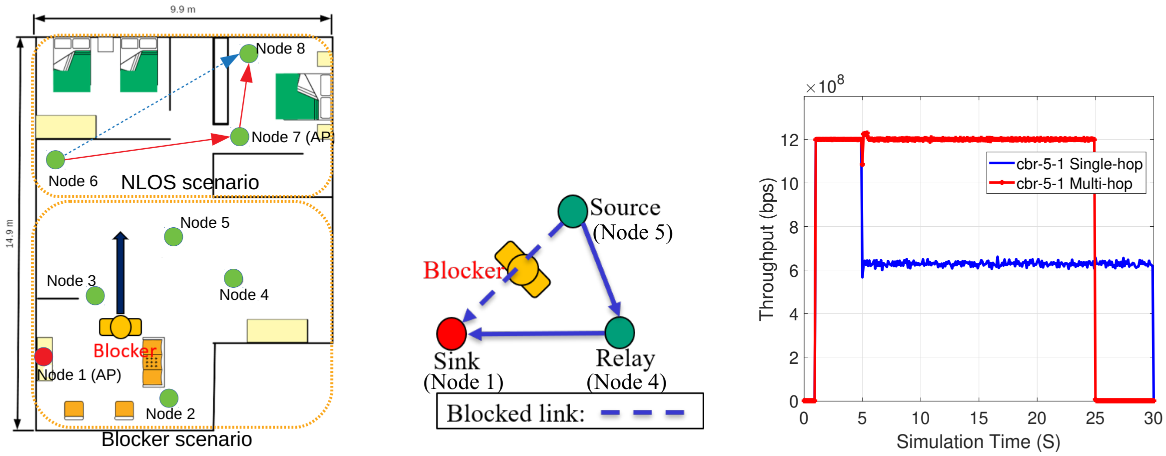
Destination STA receives potentially several RREQ messages, and sends an RREP frame to the same STA from which an RREQ was received. Each intermediate STA that receives an RREP message, updates its routing table to the destination STA. If the intermediate STA receives more than one RREP, it picks the best RREP frame and forwards it to its 1-hop neighbor STAs. Intermediate STA records the forwarding operation in its Forwarding Table. Similar to RREQ, each RREP frame and its duplicate versions determine the next-hop and backup next-hop. The process of forwarding RREP continues until the RREP message is received at the originating STA. Originating STA potentially receives more than one RREP message. It picks the best and second best RREP message and records them as the next-hop and backup next-hop to reach to the destination STA. Each STA proactively makes sure its routing table entries are up-to-date and two next-hop options are reachable.

**Route Discovery Triggers:** We use three mechanisms to detect that a neighbor STA is no longer available. First, similar to the AODV protocol, we use HELLO messages such that if a neighbor STA misses HELLO transmissions, that neighbor STA is assumed to be not available. Second, if the number of transmissions for a frame exceeds a threshold, the link is assumed to be broken. This threshold is set to 7 for short frames and 4 for long frames. Third, we implement a trigger based on the modulation and coding scheme (MCS) index such that if the MCS index drops below a specified value[1], we consider that link not useful, and route discovery process (i.e., sending RREQ) is initiated. This in turn, can guarantee a minimum throughput at the destination STA.

## III. Simulation Results

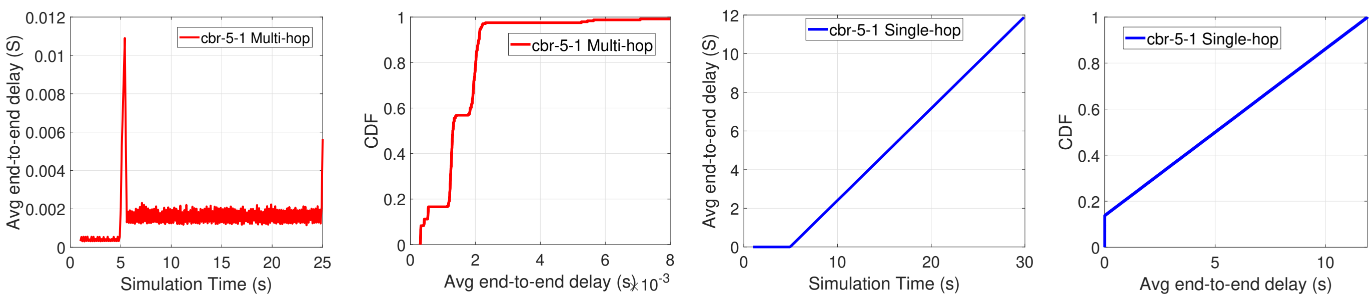
In this section, we present simulation results to investigate performance and demonstrate the benefits of multi-hop communications for indoor 60 GHz systems. We consider a mmWave network where all nodes are equipped with the IEEE 802.11ad PHY and MAC specifications. The IEEE 802.11ad SC PHY with AWGN channel model is used such that the simulation parameters are summarized in Table I.

[1] We assume that an adaptive rate controller such as ARF is deployed.




(a) Location of the nodes (b) Multi-hop topology (c) Throughput of multi-hop vs. single-hop

Fig. 1: An indoor mmWave network where node 5 is the source and node 1 is the destination. Human blockage starts at 5 seconds.




(a) Multi-hop delay (b) CDF for multi-hop delay (c) Single-hop delay (d) CDF for single-hop delay

Fig. 2: Multi-hop vs single-hop delay performance under blocker scenario with one constant bit rate (CBR) data flow from 5 to 1 (cbr-5-1).

In order to model the propagation environment, we use Remcom X3D ray tracer with High Fidelity Propagation Model (HFPM) enabled. Materials used for simulating the room environment are brick wall, concrete wall, wood, and glass. The dielectric properties of these materials are reported in [17]. In the simulations, we set the total number of computed paths to be 25; number of reflections 3, number of diffraction 1, and number of transmissions 3. We investigate throughput, end-to-end delay, and cumulative distribution function (CDF) for delay.

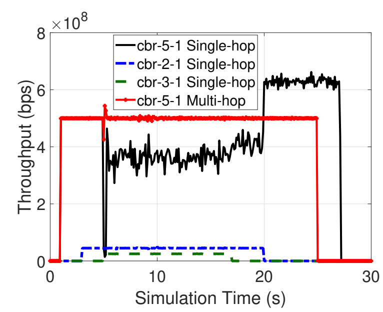
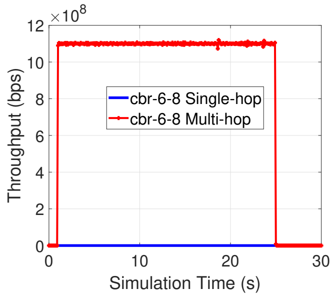


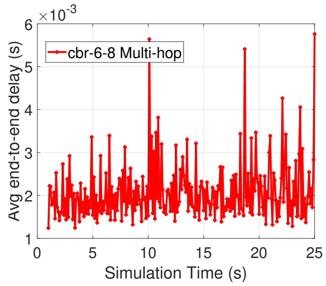

Fig. 3: Throughput comparison of multi-hop vs. single-hop

### *A. Blocker Scenario*

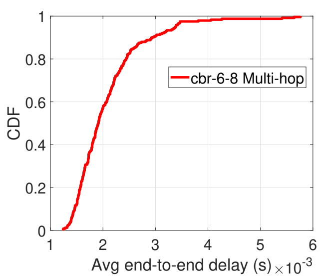
We start with a mmWave network with three nodes 1, 4, and 5 (as shown in Figure 1a) where node 5 is the source and node 1 (AP) is the destination of 1.2 Gbps constant bit rate (CBR) traffic. For this set of simulation, other nodes are inactive. At time 5s, the link between the source and destination (sink) node is blocked by a human body that is modeled as an additional 20 dB path loss. Figure 1b graphically shows the network topology and blocking object. To reach to node 1, the routing table at node 5 has node 1 as the primary next-hop and node 4 as the backup next-hop. Figure 1c shows the throughput performance of single-hop and multi-hop communications under blockage. From the results, we notice that when blockage starts single-hop link uses a lower MCS and thus throughput drops. On the other hand, multi-hop topology is able to maintain the high-throughput performance by exploiting the relay node. Figure 2a through 2d show the end-to-end delay and CDF for the delay under single-hop and multi-hop topologies. Multi-hop delay performance is considerably better than single-hop delay, with the $99^{th}$ percentile of less than 5ms. Our simulation results show that after blockage at 5s, the multi-hop protocol adds an alternative route at 5.012s. Next, we activate data flows from node 3 and node 2 to node 1 (AP). The CBR data rates are reduced to be within the capacity region, and are set to 500 Mbps




(a) Throughput performance of multi-hop vs single-hop




(b) Multi-hop delay




(c) CDF for multi-hop delay

Fig. 4: Performance of multi-hop vs single-hop for NLOS

from 5 to 1, 45 Mbps from 2 to 1, and 25 Mbps from 3 to 1. Figure 3 shows the throughput performance of single-hop and multi-hop networks. In the presence of other data flows, single-hop topology does not provide a reliable and stable throughput even at a lower data rate. On the other hand, multi-hop topology enhances the throughput performance.

### *B. Non-Line-of-Sight (NLOS) Scenario*

In this set of simulations, we examine the performance of multi-hop routing for range extension and NLOS scenarios. As shown in the *NLOS scenario* in Figure 1a, we consider a scenario such that there is no direct path between the source node 6 and destination node 8. Data traffic generated at the source is 1.1 Gbps. From the simulation results shown in Figure 4a, it is clear that direct communication between the source and destination is not able to provide sufficient link budget, and thus throughput is zero. On the other hand, multi-hop communication provides high throughput. Delay performance of multi-hop is shown in Figures 4b and 4c that we observe the latency is almost always less than 5ms.

## IV. Conclusion

In this paper, we investigated the benefits of network layer solutions and on-demand routing protocol with backup routes to ensure reliable and robust mmWave communication under severe conditions (blockage and NLOS). Our hop-by-hop multi-path routing protocol establishes one primary and one reserved link per destination such that once the primary link is blocked, the backup link is ready to be deployed. To verify the performance of our protocol, we conducted system-level simulations based on the IEEE 802.11ad PHY and MAC specifications. Our simulations confirm the validity of our approach to sustain high throughput and low latency performance under blockage and NLOS scenarios.

## Acknowledgements

This work was supported in part by the Sony corporation, NSF grants CNS-1948511 and CNS-1955561.

## References

[1] C. Slezak, V. Semkin, S. Andreev, Y. Koucheryavy, and S. Rangan, "Empirical effects of dynamic human-body blockage in 60 GHz communications," *arXiv preprint arXiv:1811.06139*, 2018.

[2] T. S. Rappaport, S. Sun, R. Mayzus, H. Zhao, Y. Azar, K. Wang, G. N. Wong, J. K. Schulz, M. Samimi, and F. Gutierrez, "Millimeter wave mobile communications for 5G cellular: It will work!," *IEEE access*, vol. 1, pp. 335–349, 2013.

[3] S. Rangan, T. S. Rappaport, and E. Erkip, "Millimeter wave cellular wireless networks: Potentials and challenges," *arXiv preprint arXiv:1401.2560*, 2014.

[4] H. Shokri-Ghadikolaei, C. Fischione, P. Popovski, and M. Zorzi, "Design aspects of short-range millimeter-wave networks: A mac layer perspective," *IEEE Network*, vol. 30, no. 3, pp. 88–96, 2016.

[5] "IEEE 802.11 TGay Use Cases." IEEE 802.11-15/625r7.

[6] H. Singh and S. Singh, "Smart-Aloha for Multi-Hop Wireless Networks," *Mobile Networks and Applications*, vol. 10, no. 5, pp. 651–662, 2005.

[7] G. Jakllari, W. Luo, and S. V. Krishnamurthy, "An Integrated Neighbor Discovery and MAC Protocol for Ad Hoc Networks Using Directional Antennas," *IEEE Transactions on Wireless Communications*, vol. 6, no. 3, pp. 1114–1024, 2007.

[8] Y. Niu, Y. Li, D. Jin, L. Su, and D. Wu, "Blockage robust and efficient scheduling for directional mmWave WPANs," *IEEE Transactions on Vehicular Technology*, vol. 64, no. 2, pp. 728–742, 2014.

[9] H. Gossain, T. Joshi, C. D. M. Cordeiro, and D. P. Agrawal, "DRP: An efficient directional routing protocol for mobile ad hoc networks," *IEEE Transactions on Parallel and Distributed Systems*, vol. 17, no. 12, pp. 1438–1541, 2006.

[10] Z. Genc, U. H. Rizvi, E. Onur, and I. Niemegeers, "Robust 60 GHz indoor connectivity: Is it possible with reflections?," in *2010 IEEE 71st vehicular technology conference*, pp. 1–5, 2010.

[11] W. Qingqing and Z. Rui, "Towards smart and reconfigurable environment: Intelligent reflecting surface aided wireless network," *arXiv preprint arXiv:1905.00152*, 2019.

[12] G. Yao, M. Hashemi, and N. B. Shroff, "Integrating sub-6 GHz and millimeter wave to combat blockage: Delay-optimal scheduling," *arXiv preprint arXiv:1901.00963*, 2019.

[13] M. Hashemi, C. E. Koksal, and N. B. Shroff, "Out-of-band millimeter wave beamforming and communications to achieve low latency and high energy efficiency in 5G systems," *IEEE Transactions on Communications*, vol. 66, no. 2, pp. 875–888, 2018.

[14] Z. Lan, C. Sum, J. Wang, T. Baykas, F. Kojima, H. Nakase, H. Harada, and S. Kato, "Achieving Gbps Throughput for Millimeter-Wave WPAN with an Anti-Blocking Scheme Using Deflection Routing," in *IEEE 70th Vehicular Technology Conference Fall*, pp. 1–6, 2009.

[15] K. Schneider, B. Zhang, and L. Benmohamed, "Hop-by-hop multipath routing: Choosing the right nexthop set," *ArXiv*, vol. abs/1906.10266, 2019.

[16] W. K. Lai, S.-Y. Hsiao, and Y.-C. Lin, "Adaptive backup routing for ad-hoc networks," *Computer Communications*, vol. 30, no. 2, pp. 453 – 464, 2007.

[17] C. Samarathunga, M. Abouelseoud, K. Sakoda, and M. Hashemi, "On the Benefits of Multi-hop Communication for Indoor 60 GHz Wireless Networks," *arXiv preprint arXiv:2009.00205*, 2020.