Multi-hop Routing with Proactive Route Refinement for 60 GHz Millimeter-Wave Networks

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***Abstract*—Fundamental requirements of millimeter wave (mmWave) systems are peak data rates of multiple Gbps and latencies of the order of at most a few milliseconds. However, highly directional mmWave links are susceptible to frequent link failures under stress conditions such as mobility and human blockage. Under these conditions, multi-hop routing can achieve reliable and robust performance. In this paper, we consider multi-hop mmWave systems and propose proactive route refinement schemes under dynamic scenarios. First, we consider the AODV-type protocols and propose a cross-layer approach that integrates sectorized communication at the MAC layer with on-demand multi-hop routing at the network layer. Next, we consider Backpressure routing protocol, and enhance this protocol with periodic HELLO status messages. System-level simulation results based on the IEEE 802.11ad standard confirm the benefits of proactive route refinement for the ADOV-type and Backpressure routing protocols.**

I. Introduction

The growing demands for applications with extremely high data rates as well as the increasing density of wireless devices are catalyzing a coming spectrum crisis in the sub-6 GHz bands. The spectrum-rich mmWave frequencies between 30 GHz to 300 GHz have the potential to alleviate the spectrum crunch that the wireless operators are already experiencing [1]. This major potential of the mmWave bands has made them the most important component of future mobile cellular and emerging WiFi networks with Gbps data rates.

Compared with the legacy wireless systems operating in the sub-6 GHz bands, there are significant challenges that need to be overcome before practical mmWave systems can be commercialized. Propagation loss at mmWave frequencies is much higher due to a variety of factors including atmospheric absorption and low penetration. In addition to large path losses, due to small wavelengths in the mmWave band, most objects such as human body can significantly attenuate the mmWave signals (up to 20 dB), which can entirely break the link. To mitigate the blockage issue, there are several proposals on exploiting reflection paths from walls [2], using intelligent reflecting surfaces [3], and integrating mmWave with lower frequencies [4, 5]. One effective approach to combat blockage in mmWave is to leverage multi-hop routing. In [6], the authors propose a hop-by-hop multi-path routing protocol that is efficient and fast in switching to a reserved ready-to-use path towards the destination. However, due to the dynamic conditions in mmWave propagation environment, it is highly likely that the blockages are temporary and highly dynamic. Thus, it is desirable that multi-hop routes towards the destination be refined within a shorter period of timescale compared with the routing table reset timescale across the network. In this paper, we propose proactive route refinement schemes for multi-hop mmWave networks by considering two general classes of multi-hop routing protocols: (i) *AODV-type protocols* that are based on distributing route request (RREQ) and route reply (RREP) messages, and (ii) *Backpressure-type protocols* that are built upon finding the best route based on local information at each node [7].

In order to achieve proactive route refinement for the AODV-type protocols, we pose the following question: *given that the sector sweep operation is needed for establishing and maintaining directional mmWave links, is it possible to leverage sector sweep (SSW) frames for routing purposes?* By carefully integrating the route request and route reply messages with sector sweep frames, we achieve a proactive route refinement step that can be added to on-demand AODV-type routing protocols. Leveraging sector sweep frames results in more optimized routes without sending more control messages. In this case, SSW frames will be longer since route refinement fields piggyback on the SSW frames.

In the backpressure-type protocols, there is no explicit route request or route reply messages (as described in Section IV). Instead, each node selects one of its neighbors with the maximum backpressure weight and forwards packets to that neighbor. In omni-directional wireless systems, nodes can overhear other nodes' transmission and extract relevant information that are needed for calculating the backpressure weight. However, this mechanism does not work in mmWave networks due to directionality. Therefore, we propose integrating periodic HELLO messages into backpressure to distribute the parameters that are needed for calculating backpressure weight. This periodic status update message provides the possibility of refining multi-hop routes based on fresh information.

We implement the proposed route refinement mechanisms and multi-hop protocols for system-level evaluations. The simulation setup is mainly focused on indoor 60 GHz systems where 7 GHz unlicensed band is available. In summary, the main contributions of this work are as follows: (i) we propose a cross-layer route refinement mechanism for AODV-type protocols, and integrate a periodic status message into the Backpressure protocols, and (ii) we implement the AODV and Backpressure protocols on top of the IEEE 802.11ad standard to demonstrate the benefits of route refinement.

II. Background and Related Work

In general, AODV-type protocols use route request (RREQ) and route reply (RREP) messages to establish multi-hop routes between the source STA and the destination STA. There have been several works to customize the AODV protocol for directional communications. The authors in [8] evaluate the performance of dynamic source routing (DSR) protocol when executed over directional antennas. The work in [9] proposes a Directional Routing Protocol (DRP) that couples some aspects of the routing layer with the MAC layer. The authors in [10] provide a comparative view for several directional routing protocols, including DRP, Directional Dynamic Source Routing (DDSR), Directional Ad-hoc On-demand Distance Vector (DAODV), Energy Efficient Directional Routing (EEDR), and Directional Antenna Multipath Location Aided Routing (DA-MLAR). Moreover, [11] proposes an adaptive MAC protocol, where each node keeps certain neighborhood information dynamically through the maintenance of an Angle-SINR table, which can improve the performance of directional routing protocols. Another directional routing protocol is proposed in [12] that is based on the angle of arrival estimation such that the routing paths are chosen to minimize interference.

Our Contributions: Complementing the previous works on directional multi-hop routing, this paper is aimed to answer this question: *how can we achieve proactive route refinement for on-demand routing protocols?* Route refinement is essential for on-demand protocols since mmWave link blockage can be temporary and highly dynamic. For instance, the authors in [13] have shown that the LOS blockage on average lasts for about $1/\mu$ seconds, where $\mu = 2$ is used in their numerical results [13]. By deploying an on-demand routing protocol, the source node has already established a route toward the destination via the relay STA. Thus, the source node would not search for a better route (in terms of a pre-defined route metric) until the next network-wide routing tables reset. Therefore, it is desirable to provide agile route refinement solutions under dynamic blockage scenarios. For the AODV-type protocol, we propose to leverage the SSW frames that are being sent according to a transmit schedule. The enhanced SSW frames carry routing-related fields and elements. For the Backpressure-type protocol, we integrate a periodic HELLO message that is sent to the neighbor nodes.

III. Cross-Layer Route Refinement for AODV

In order to quickly establish a multi-hop route toward the destination, the originating STA sends route request (RREQ) to its neighbor STAs, assuming that the STAs have performed the SSW beforehand, and that there are periodic sector sweep operation for link maintenance purposes. To utilize SSW frames for route refinement, we propose the following protocol: by deploying an on-demand routing protocol, the source STA takes three steps: (1) it sends the RREQ frame toward the relay node (i.e., the normal operation of the on-demand routing), (2) it extracts and stores the RREQ elements, and (3) it will use the RREQ elements at the next SSW transmission opportunity. At the next SSW interval, the source

Algorithm 1 Enhanced-SSW – Initiator

```
S: set of neighbor nodes
function TRANSMIT SECTOR SWEEP
    if RREQ is received from the Network layer then
        Add RREQ fields to legacy SSW frame
        Create an Enhanced-SSW frame
        Set transmitFrame = Enhanced-SSW frame
    else
        transmitFrame = Legacy-SSW frame
    end if
    for neighbor node i ∈ S do
        Send transmitFrame to node i
    end for
end function

function RECEIVE SECTOR SWEEP FEEDBACK
    Process the frame to update sectors information
    if Enhanced-SSW feedback frame is received then
        Extract routing fields and update the routing table
    end if
end function
```

Algorithm 2 Enhanced-SSW – Respondor

```
function RECEIVE SECTOR SWEEP
    Receive the transmitted sector sweep frames
    if Enhanced-SSW frame is received then
        Extract routing fields
        Query local routing table
        Embed routing information in an Enhanced sector sweep feedback frame
    else
        Reply with legacy sector sweep feedback frame.
    end if
end function
```

STA adds the RREQ elements to the SSW frames. We refer to this type of the SSW frame as *Enhanced-SSW* frame. The responder node receives the Enhanced-SSW frames across different sectors, extracts the route discovery elements, and queries its routing table for finding a potential route toward the destination requested through the Enhanced-SSW frames. The responder node replies to the transmitter node with the Enhanced-SSW reply frames, which potentially includes route information toward the destination. Enhanced-SSW frames are received by the source node that extracts route information and updates its routing table. Note that this sector sweep operation is performed with all neighbor nodes. As a result, sector sweep frames – which are used for establishing/maintaining directional links – can potentially lead to refined and optimized multi-hop routes toward the destination. Algorithms 1 and 2 summarize the steps at the initiator and respondor STAs.

Figure 1 shows the sequence diagram of the implementation, where RREQ messages are passed to the MAC layer, embedded in the SSW frames, and received by a neighbor STA or access point (AP). In response, the neighbor STA

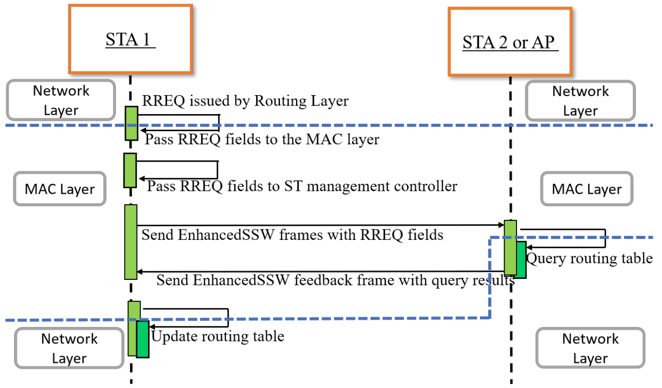


Fig. 1: Message sequence diagram for integrating the SSW frames and route refinement messages.

or AP queries its own local routing table, and embeds the query results in the reply SSW frames. Upon receiving the reply SSW, the initiator STA updates its routing table. We see that there are several rounds of cross-layer message passing at the initiator and responder nodes. From these steps, we note that route refinement messages piggyback on the SSW frames, and thus they do not introduce overheads in terms of the number of messages. The overhead of transmission and reception of routing control messages is translated to function calls between the MAC layer and routing layer at the STA nodes, i.e., query and update the routing table. This method achieves a cross-layer route refinement for directional communication. However, it should be noted that adding RREQ/RREP increases the size of legacy SSW frames.

Discussion: Beam refinement and tracking are also utilized under dynamic and mobile scenarios for link maintenance. In this paper, we only consider leveraging the SSW frames for route refinement, and beam refinement integration with routing operation is out of the scope of this work. Moreover, we note that the route refinement is performed at the link layer and on a per-link basis, meaning that Enhanced-SSW frames can be exchanged between the source and relay node, two relay nodes, or relay and destination node. Therefore, the proposed scheme is not limited to the last hop only. If the responder STA does not have more-optimized route information to send to the initiator, then Enhanced-SSW frame exchange would not modify the routing table at the initiator STA.

IV. Route Refinement for Backpressure Protocol

Backpressure routing algorithm is based on solving a problem known as MaxWeight, where the goal is to maximize the weighted sum of link rates. The weights are defined by backlog differentials between neighbor nodes [14]. Backpressure algorithm leads to the problem of minimizing the Lyapunov drift that is defined as the difference between the values of the Lyapunov function at the current time slot and at the next time slot. In order to solve the MaxWeight problem, intuitively data packets are sent over links with high rates and to neighbors with small queue lengths. For instance, Backpressure Collection Protocol (BCP) [7] is one version

Algorithm 3 mmWave-BCP

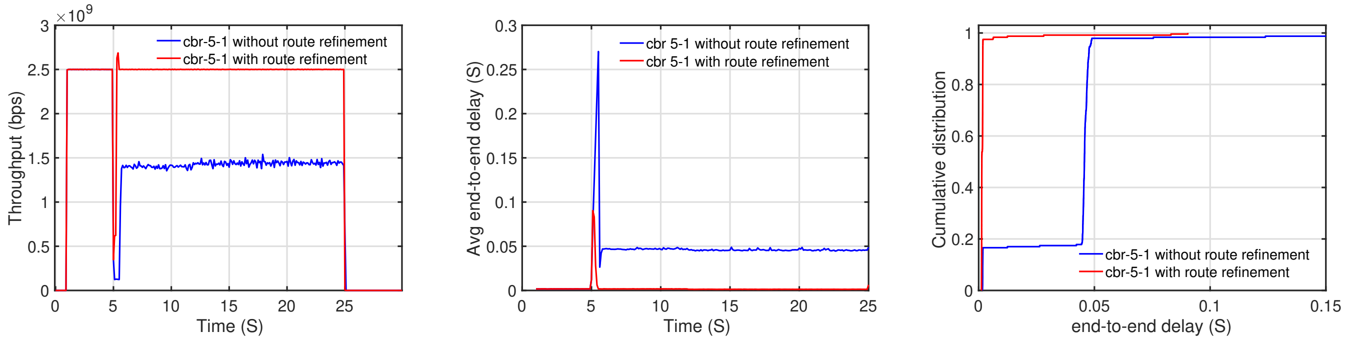
1: $\mathcal{S}_i$: Set of neighbor nodes for node i
2: **for** $j \in \mathcal{S}_i$ **do**
3: Receive periodic HELLO message from node j
4: Compute backpressure weight $w_{i,j}$ for neighbor j
5: Find the neighbor j^* such that $j^* = \arg\max_j w_{i,j}$
6: **if** $w_{i,j^*} > 0$ **then**
7: Transmit packets to j^* until the next HELLO interval
8: **else**
9: Wait for a reroute period and go to line 3
10: **end if**
11: **end for**

of the backpressure algorithm that can be implemented in a distributed manner. Then, each node independently makes routing decisions based on local information. Let Q_i represent the queue length at node i. Then $\Delta Q_{i,j} = Q_i - Q_j$ is the queue differential (backpressure) between node i and its neighbor node j. Let $\overline{\mathcal{R}}_{i\to j}$ denote the estimated link rate from i to j and $\overline{ETX}_{i\to j}$ be the average number of transmissions for a packet to be successfully sent over the link. In the routing policy of BCP, node i calculates the following backpressure weight for each neighbor j:

$$w_{i,j} = (\Delta Q_{i,j} - V \cdot \overline{ETX}_{i\to j}) \cdot \overline{\mathcal{R}}_{i\to j}, \tag{1}$$

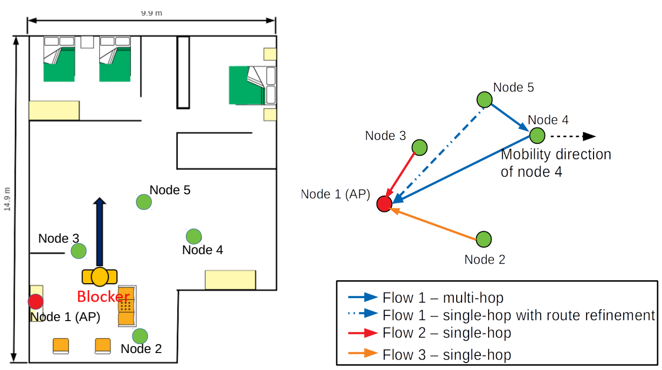
where $V > 0$ is a non-negative control parameter to adjust the importance of the penalty function $\overline{ETX}_{i\to j}$. The routing decision (next hop of the packet) is determined by finding the neighbor j^* with the highest weight. Then the node needs to make the forwarding decision: if $w_{i,j^*} > 0$, the packets are forwarded to node j^*.

In omni-directional systems, in order to disseminate all the necessary information to compute backpressure weights, BCP header fields include local queue information that are broadcasted. Therefore, all nodes within reception range of the transmitter receive and process the BCP packet header through the snoop interface. This method, however, does not work for mmWave systems due to directionality of transmission and reception. In addition, in contrast to the AODV protocol, there is no RREQ/RREP messages in BCP since routing is achieved based on local information of each node from its neighbor nodes. In order to achieve proactive route refinement for BCP, we propsoe to add a periodic HELLO message to the original BCP protocol. Thus, all the necessary information to compute weights is exchanged amongst nodes by means of periodic emission of HELLO messages. It should be noted that under dynamic scenarios where nodes are joining or leaving the network or blockage occurs frequently, the HELLO interval needs to be set to a small value. On the other hand, a larger HELLO interval will be sufficient for more stationary network conditions. In Section V, we examine different values of HELLO interval and its effect on the system performance. Algorithm 3 summarizes the mmWave-BCP protocol.



(a) *Throughput performance* (b) *Delay performance* (c) *CDF of delay*

Fig. 2: Performance of **AODV routing protocol** with and without route refinement using sector sweep frames. Blockage lasts for 200ms.



(a) Indoor mmWave setup (b) Network topology and data flows

Fig. 3: Indoor mmWave network with a human blocker and mobility.

TABLE I: Simulation parameters

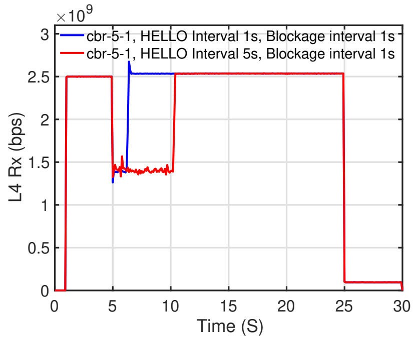
Simulation Parameter	**Value**
Transmit power	18dBm
Preamble detection threshold	-68dBm
Noise level	-70.6dBm
Energy detection threshold	-48dBm
Channel access scheme	Contention based
Beacon interval (BI)	100ms
Beacon header interval (BHI)	5ms
Data transmission interval (DTI)	95ms
Rate controller	ARF
Maximum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

V. Simulation Results

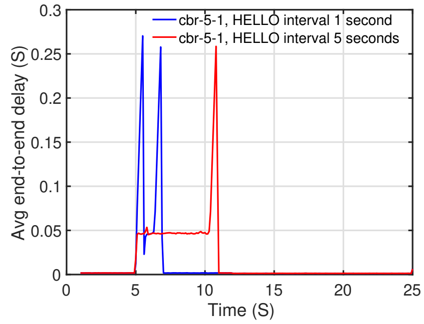
To demonstrate the benefits of on-demand routing with proactive route refinement, we consider a mmWave network as shown in Figure 3a that includes human blockage and node mobility. Nodes 1, 2, 3 and 5 are stationary, and node 4 is mobile with the mobility pattern shown in Figure 3b. All nodes are equipped with the IEEE 802.11ad MAC and SC PHY specifications with AWGN channel model. Also, we assume that all nodes in the network are capable of sending and receiving Enhanced-SSW frames. The simulation parameters are summarized in Table I. To model the propagation environment, we use Remcom X3D ray tracer with High Fidelity Propagation Model (HFPM) enabled. The total number of computed paths is set to 25 with the number of reflections 3, number of diffraction 1, and number of transmissions 3.

Blocker Scenario with Node Mobility and Single Data Flow: First, we activate nodes 1, 4 and 5, while nodes 2 and 3 are not active. Human blockage is modeled as an additional 20 dB path loss that is applied at time 5s. To model dynamic changes in the environment, the link between the source and destination (sink) node is blocked for 200ms, and after that the blockage is removed. The generated traffic data rate at node 5 is 2.5 Gbps with a constant bit rate (CBR) pattern. Figure 2a depicts the throughput performance measured at node 1. Before time 5 seconds, node 5 transmits directly to node 1 and the achieved throughput is 2.5 Gbps. Once the blockage happens, the AODV routing protocol kicks in to find an alternative route toward the destination node, in which case the data traffic is routed to node 4 as a relay node. From the results, we see that if there is no route refinement, the throughput remains the same even after the blockage is removed. On the other hand, once the blockage is removed at 5.2 second and by activating the proactive route refinement, node 5 can switch back to a single-hop route by directly transmitting to node 1 and achieving the 2.5 Gbps throughput. Note that this route refinement step is achieved by the sector sweep operation between node 5 and node 1 once the blockage has been removed. Therefore, no additional signal exchanges is needed. Figure 2b and 2c compare the delay and CDF of delay for multi-hop routing with and without route refinement. From the results, we observe that route refinement significantly improves the delay performance. Next, we deploy the mmWave-BCP routing protocol and investigate route refinement using HELLO packets in order to distribute up-to-date queue length and data rate information for calculating the backpressure weights. In this simulation, we increase the blockage duration to 1 second (i.e., between 5 to 6 seconds). The results shown in Figure 4 depicts the throughput, delay, and delay CDF for two HELLO intervals of 1 and 5 seconds. From the results, we observe that HELLO messages play an important role to find and switch back to a single-hop topology when the blockage is removed.

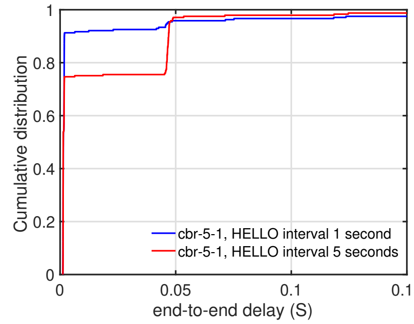
Blocker Scenario with Multiple Data Flows: The data



(a) *Throughput performance*



(b) *Delay performance*



(c) *CDF of delay*

Fig. 4: Performance of **Backpressure routing protocol** with different HELLO intervals. Blockage lasts for 1s.

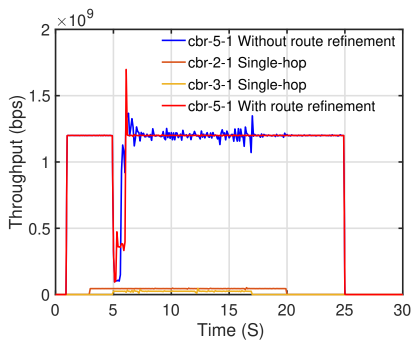


Fig. 5: Throughput performance of **AODV protocol** with multiple data flows, and with and without route refinement using SSW frames.

flows from node 3 and node 2 to node 1 (AP) are activated. Data rates are reduced to be within the capacity region, and are set to 1.2 Gbps from 5 to 1, 45 Mbps from 2 to 1, and 25 Mbps from 3 to 1. Figure 5 shows the throughput performance of single-hop and multi-hop networks with and without route refinement. There are fluctuations in the throughput from 5 to 1 without route refinement under multi-hop topology. On the other hand, we observe that the throughput is more stable with route refinement when the topology switches back to single hop (i.e., once the blockage is removed).

VI. Conclusion

In this paper, we proposed proactive route refinement schemes for AODV and Backpressure routing protocols. For the AODV protocol, we utilize sector sweep frames to transmit route request and route reply fields at each SSW interval. As a result, multi-hop routes that have already been established by the on-demand routing protocol, are proactively refined using sector sweep frames in order to find more optimized routes as blockage dynamically changes. Our simulation results demonstrate that such a cross-layer protocol enhances the delay and throughput performance compared with when the route refinement is not activated. For the Backpressure protocol, we proposed adding a periodic HELLO messages to distribute the necessary information needed to compute backpressure weights. Throughput and delay simulation results clearly demonstrate the role of the HELLO interval to achieve agile route refinement in Backpressure protocol.

Acknowledgements

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