# MULTIPATH HYBRID AD HOC NETWORKS FOR AVIONICS APPLICATIONS IN DISASTER AREA

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## Abstract

During natural or manmade disasters, communication infrastructures break down due to massive destruction and subsequent loss of services. Effective rescue operations require a rapidly deployable high bandwidth network to carry out necessary relief efforts involving helicopters up in the sky and first responders on the ground. However, transmitting video and running high bandwidth applications over the network consisting of if RF (Radio Frequency) links is challenging. Our aim is to develop an avionics system consisting of a fast, high bandwidth, self configurable and reliable network for rapidly establishing communication among the helicopters and first responders in a disaster area. The concept of using FSO (Free Space Optics) link as the primary and RF as the backup link has been introduced in this paper. We develop an Ad Hoc routing protocol for computing multiple "FSO only" paths to ensure faster communication among the nodes, and using "hybrid paths" consisting of a mixture of FSO and RF links as a backup. Our routing protocol, referred to as Ad hoc On-demand Distance Vector Hybrid (AODVH), has been compared with other Ad hoc Routing protocols using ns-2 simulations. It was found that AODVH performs better than others in terms of percentage of packet loss, average delay and throughput.

**Keywords**: Ad hoc routing, avionics, FSO, multipath routing, disjoint paths

## I. Introduction

Natural or manmade disasters take heavy tolls on lives and properties. Communication infrastructures break down, and lack of communication affects the search and rescue operation adversely. During Hurricane Katrina we have seen that thousands of people suffered due to the lack of coordination among the relief organizations and one of the main reasons for this remains the destruction of communication channels in that area. The need for a rapidly deployable network is thus needed during state of emergency. Our aim is to develop an ad hoc network for a quickly deployable, reliable and high bandwidth communication infrastructure, which will re-establish communication following a disaster, among helicopters and ground responders to carry out necessary relief efforts. Our proposed network architecture is called Disaster Area Wireless Network (DAWN).

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An Ad Hoc network is a quickly deployable network consisting of a set of mobile nodes with no base station or infrastructure support [1]. Without any centralized administration, each node has limited battery power, processing power and on-board memory. A Mobile Ad Hoc Network (MANET) is characterized by dynamic topologies due to uncontrolled node mobility (helicopter movement in the case of DAWN), limited and variable shared wireless channel bandwidth, and wireless devices constrained by battery power [2]. Nodes in an Ad Hoc network communicate using RF links in a multihop (hop to hop) fashion using unipath routing protocols. RF links have lower bandwidth (as compared to optical links) and, therefore, Free Space Optical (FSO) links are more suitable for high bandwidth applications, such as video or voice, required by rescue teams during recovery operations [3]. A key challenge in such networks is to design a dynamic routing protocol using hybrid links, with Free Space optical links as the primary medium of communication and RF as backup when FSO links fail.

Our *objective* here is to develop a multipath, on-demand, distance vector routing protocol for Hybrid nodes (with FSO and RF links) called Ad hoc On-demand Distance Vector Hybrid (AODVH).

In this paper, we address the issue of multipath routing over hybrid nodes for DAWN, with a view to maximize the overall performance. Multiple routes minimize route discovery time and control overhead [4]. Multipath routing in AODVH has the following advantages [5, 6]:

- Increases the reliability of data transmission (fault tolerance) in a network;
- Improves the effective bandwidth of communication pairs; and
- Flexibility in responding to congestion and traffic.

AODVH differs from other Ad Hoc routing protocols (DSR [7], OLSR [8], AODV [9]) which are designed for single path and hence require significant time to find a new route in case of link failures. Due to the intermittent characteristics of FSO links, the large rerouting time of single path protocols are not suitable for FSO links.

Though on-demand protocol, for example, TORA [10] has the option for multipath but TORA requires reliable and in-order delivery of routing control packets and coordination among nodes with frequent changes in topologies. These requirements hurt the performance of TORA to a point where the advantage of having multipath is undermined [2].

The existing multipath routing algorithms for Ad Hoc networks in literature such as Split Multipath Routing (SMR) [1], AODVM [11], and AOMDV [12], are extensions of unipath routing protocols viz. DSR (Dynamic Source Routing) [7] and AODV [9]. Lee et al. [1] developed a split multipath routing protocol with maximally disjoint paths for RF nodes. Marina et al. [2] developed a loop free and link-disjoint multipath routing protocol (AOMDV) to achieve improvement in the end-to-end delay with homogeneous RF nodes. Zhenqiang et al. [11] proposed a routing protocol (AODVM) to discover multiple node-disjoint paths from a source to a destination to achieve reliability in path setup for RF nodes. AODV-BR [13] is an extension to AODV that uses backup routes that are maintained through overhearing at the neighboring nodes in case of primary route failure. Locally broadcast messages are propagated in the intermediate nodes to salvage the data packets when primary route fails. Another protocol, called CHAMP [14] creates and maintains shortest multipath that are loop free at each node. It is to be noted that all of the above are based on homogeneous nodes and are *not suitable* for hybrid nodes.

There exists research works on Free Space Optics in literature. Bilgi et al. [15] proposed a simulation model for pure FSO node structures with intermittent connectivity pattern. Yuksel et al. [16] proposed a new FSO node design that uses spherical surfaces covered with transceiver models to maintain optical links when the nodes are in relative motion. These research works only considered optical links and hence did not meet our requirements.

Gurumani et al. [17] demonstrated dynamic path reconfiguration of hybrid nodes in the testbed by blocking different transceivers of the nodes. Some simulation studies on performance and throughput evaluation of hybrid FSO/RF links were performed by Wu et al. [18]. Kashyap et al. [19] developed a routing algorithm for obscured traffic in hybrid RF/FSO networks. It is to be noted that the above works did not provide multipath routing algorithms while providing highest FSO network potential.

Our proposed protocol AODVH *differs* from the other multipath routing protocols because it uses *heterogeneous* links consisting of FSO and RF links. The protocol uses “FSO only paths” as the primary path, with “Hybrid” paths of RF and FSO links as backup/fallback option. Existing multipath protocols [1, 2, 11, 12, 13, 14] are designed for homogeneous nodes and hence cannot differentiate between primary and secondary path which may significantly differ in terms of bandwidth. The main *contribution* of this paper is to develop an Ad Hoc routing protocol for computing multiple “FSO only” paths to ensure faster communication among hybrid nodes using FSO and RF links in DAWN.

The rest of the paper is organized as follows. Section II discusses related work. We describe our proposed network architecture in Section III. In Section IV, we develop our proposed AODVH protocol. Section V compares the performance of AODVH with AODV and AOMDV. Section VI presents our conclusions.

## II. Related Work

The idea of on-demand routing protocols (e.g. DSR [7], OLSR [8], TORA [10], AODV [9]) for mobile ad hoc networks (MANETs) has been developed with the goal of minimizing the routing overhead. In contrast to proactive routing protocols (e.g. DSDV [20]), which maintain all routes regardless of their usage, on-demand or reactive routing protocols compute routes only when they are needed [2]. In reactive routing protocols, the source initiates route discovery process by sending Route Request (RREQ) to the destination. Flooding is used to broadcast the route requests. After sending the route requests, the source waits for a Route Reply (RREP) from the destination. Among the reactive routing protocols, AODV [9] minimizes routing overhead compared to DSR [7] and TORA [10] which is necessary for transfer of high bandwidth applications. In this section, we briefly discuss AODV [9] (Ad hoc On-demand Distance Vector), AOMDV [2], and AODVM [11] - two multipath extensions of AODV for computing disjoint paths.

### *A. AODV*

AODV [9] uses hop-by-hop routing by maintaining routing table entries at intermediate nodes. It combines the use of destination sequence numbers in DSDV [20] with an on-demand route discovery technique as described below:

**Route Discovery**: The route discovery process is initiated when a source needs a route to a destination but does not have a route in its routing table. The source invokes a network-wide flood of RREQ message. The RREQ packet contains information for the Destination node for which the route is requested. Additionally, each RREQ contains information about destination and source sequence numbers which are used to indicate the freshness of the route. Upon receiving a RREQ packet, a node checks to see if it is the destination or whether it has a fresh enough route to the destination. If either case is true, the node generates RREP message, which is sent back to the source along the reverse path. Each node along the reverse path sets up a forward pointer to the node from which it received the RREP. This sets up a forward path from the source to the destination. If a node is not the destination, it re-broadcasts the request message to its neighbors and keeps track of the request packet in order to set up reverse path as well as forward path.

The nodes can determine whether the route is current by comparing the destination sequence number in RREQ with that of the sequence number in the route cache. If the RREQ sequence number is greater than the one in cache, it does not send RREP to the source. Instead, it re-broadcasts the RREQ. An intermediate node only replies from its cache if the RREQ sequence number is less than or equal to the sequence number stored in the route cache. In that case the node has a "fresh enough" route and it sends RREP through the reverse path which was previously set up. When the RREP reaches the source, it starts sending data to the destination using the discovered path.

**Route Maintenance**: When a node detects a broken link while attempting to forward a packet to the next hop, it generates a Route Error (RERR) that is sent to all sources that use the broken link. The RERR packet erases all routes that use the link along the way. If a source receives a RERR and a route to the destination is still required, it initiates a new route discovery process. Also, the stale routes are deleted from the routing table if they are unused for a certain period of time.

Many multipath routing protocols based on AODV [9] have been proposed in literature. Among these protocols, AOMDV [2] offers link disjoint paths and AODVM [11] offers node disjoint paths. We are particularly interested in AODVM [] (Ad hoc On-demand Distance Vector Multipath) due to its node disjoint routes which offer high fault tolerance.

### *B. AOMDV*

AOMDV [2] shares several characteristics with AODV [9] as it is based on the distance vector concept and uses hop-by-hop routing approach. It is the multipath extension for AODV that computes multiple link disjoint paths (Figure 1).

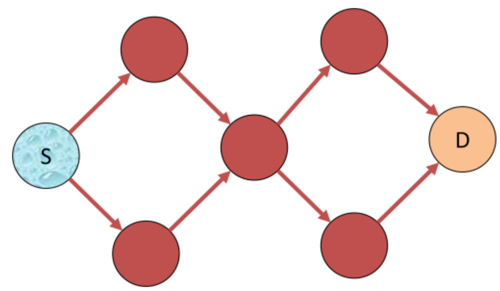


**Figure 1. Link Disjoint Paths**

**Route Discovery**: AOMDV finds routes on demand using a route discovery procedure where the main difference with AODV lies in the number of routes that are found in each route discovery. In each route discovery, multiple link disjoint paths are found from the source to the destination. In AOMDV, multiple reverse paths exist both at the intermediate nodes as well as at the destination. Multiple RREPs traverse these reverse paths to form multiple forward paths between the source and the destination [2].

AOMDV also provides intermediate nodes with alternate paths that are useful in reducing the route discovery frequency [9].

**Route Maintenance**: AOMDV route update rules are applied locally at each node which play a vital role to maintain loop-freedom and link disjointness [12]. The basis of computing link disjoint paths in AOMDV is: If there are two link disjoint paths from a source node S to a destination node D exist, then they must be having unique next hops and unique last hops. Every node on a link disjoint path ensures that all paths to the destination from that specific node have to differ in their next and last hops [2]. This multipath protocol relies as much as possible on the available routing information of AODV, thereby reducing the overhead in discovering multiple paths by adding a few extra fields in routing control packets (e.g. RREQs, RREPs and RERRs) [2].

The fault tolerance of AOMDV may be lower than AODVM because in the case of link failure (due to movement, for example), the chances of losing multiple paths are higher as one node may contain several links to form several paths.

### *C. AODVM*

AODVM [11] (Ad hoc On-demand Distance Vector Multipath) has been proposed as an extension to AODV to enable discovery of multiple node-disjoint paths (Figure 2) from a source to a destination as described below:

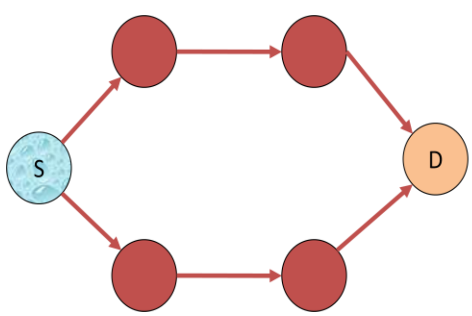


**Figure 2. Node Disjoint Paths**

**Route Discovery**: When an intermediate nodes receives multiple RREQ messages from previous nodes, instead of discarding the duplicate RREQ messages, they actually record the information of these RREQ packets in a separate table that is referred to as the “RREQ table”. For each received RREQ, the intermediate node records the source address that generated that RREQ, its corresponding destination address, the neighbor from which the node received the RREQ and other necessary information regarding the number of hops to source and expiration timer.

Unlike AODV, the intermediate nodes in AODVM refrain from sending RREP back to the originating source. This is done to make sure all the RREQ messages (including the duplicate ones) reach the destination to allow the destination to generate multiple RREP messages. When the destination receives the first RREQ message from one of its neighbors, it updates its sequence number and generates a RREP. The RREP packet contains additional information on “last hop id" to determine the neighbor from whom the corresponding copy of the RREQ was received. The RREP is sent back through the reverse path. Upon receiving duplicate RREQ messages, the destination updates it destination sequence number and generates RREP packets for all the RREQ messages [11].

**Route Maintenance:** When an intermediate node receives a RREP, it deletes the entry corresponding to this neighbor from its RREQ table. Then the node finds out the neighbor in the RREQ table from which the path to the source is the shortest and forwards the RREP through that neighbor. The entry corresponding to this neighbor is then deleted from the RREQ table. In order to ensure that an intermediate node is not involved in generating multiple RREP messages, when the other nodes overhear any node generating a RREP, they delete the entry corresponding to that node from their RREQ tables [11].

## III. Proposed Network Architecture

Our proposed network architecture shown in Figure 3, called *Disaster Area Wireless Network (DAWN)*, consists of communication nodes of helium filled balloons having routers that are tethered to the ground, helicopters, trucks and humans. The mesh of routers, in the balloons, helicopters, trucks and humans forms an Ad Hoc network, where the nodes communicate among themselves using Free Space Optical (FSO) and Radio Frequency (RF) links. . The routers are self configurable as new balloons can be deployed thus changing the network topology dynamically. This requires a careful design of the Ad

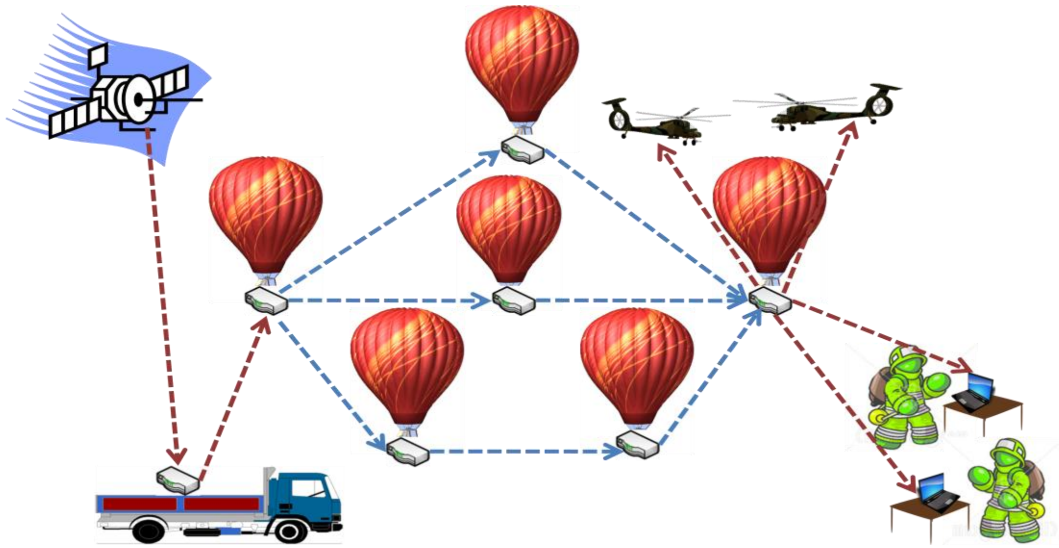

**Figure 3. Disaster Area Wireless Network (DAWN)**

Hoc network to maximize the throughput and minimize blocking probabilities.

An FSO link has significantly higher bandwidth and lower error rate when compared to an RF link [21]. However, link unavailability arising from atmospheric attenuation remains a big challenge for FSO links due to factors like absorption (caused primarily by water vapor and carbon dioxide), scattering (caused by fog) and shimmer (caused by atmospheric turbulence, air density, light refraction, cloud cover and wind) [17]. Because of this intermittent characteristic of FSO links, it is not always possible to maintain "FSO only" paths (Figure 4). As a practical solution, in DAWN we use RF links as backups. In case of unavailability of "FSO only" paths, we use "Hybrid" paths consisting of both FSO and RF links.

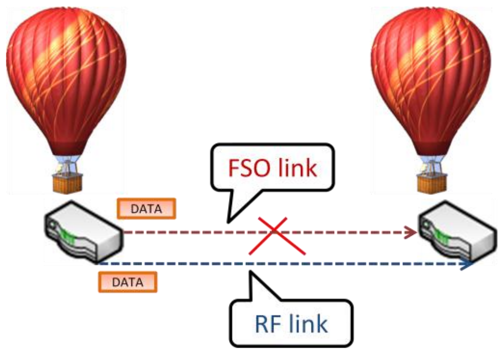


**Figure 4. Misaligned FSO Link; RF as Backup**

In addition to disaster recovery, this type of quickly deployable and high bandwidth network can be very useful in military and exploration missions. Home area wireless networking, networking intelligent devices, sensors, mobile robots, and on-the-fly conference applications can also benefit from this protocol.

# IV. Proposed Algorithm

We describe our proposed multipath Ad hoc On-demand Distance Vector Hybrid (AODVH) protocol which is based on AODV (Sec. III-A) and AODVM (Sec. III-C).

We propose modifications to AODVM [11] to enable the discovery of paths between Hybrid nodes consisting of FSO and RF links. Since FSO links have low error rates and high bandwidth, our proposed protocol, AODVH, thus attempts to establish paths consisting of "FSO only" links as the primary path.

However, due to the intermittent characteristic of FSO links, they drop in and out easily due to external conditions like fog, rain, birds' flight, etc. For this reason, our algorithm uses RF links as backup when FSO links go down. We include Hybrid paths (paths consisting of FSO and RF links) in our design as backups during FSO link failures. We implement hybrid paths by a multi interface (FSO and RF) node structure. To explain our algorithm, we use the example topology in Figure 5.

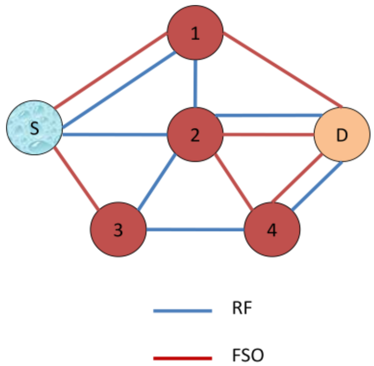


**Figure 5. Topology for AODVH**

**Route Request Message (RREQ):** The source sends RREQ message to both of the FSO (if available) and RF links. Intermediate nodes do not discard the duplicate RREQ messages; the RREQ messages from both interfaces are stored. They construct Route Request (RREQ) table and keep the information for the source, destination, and neighbor list and for each neighbor, hops to source and expiration timer to detect stale routes. During the first stage of RREQ message, nodes 1, 2 and 3 receive RREQ from the source. The RREQ table for node 1 is shown in Figure 6.

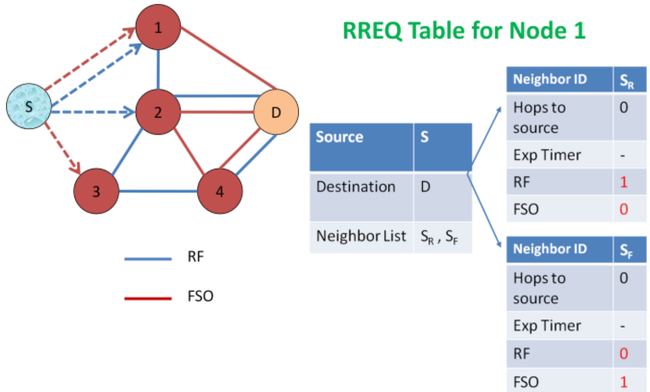


**Figure 6. RREQ Table for Node 1 (stage 1)**

Nodes 2 and 3 also set up their RREQ table the same way. During stage 2 of RREQ message, these intermediate nodes send the RREQ packets they received from the source to their neighbors. The neighbors do not discard any duplicate RREQ messages, but keep their necessary information in their respective RREQ table. The RREQ table for node 1 is shown in Figure 7.

Following this same procedure, the duplicate RREQ messages reach the destination node through all the intermediate nodes. The scenario in our case looks like Figure 8.

**Route Reply Message (RREP*)*:** Upon receiving the first RREQ, the destination node starts generating RREP. This RREP routes through the reverse path that was created during the RREQ broadcast stages.

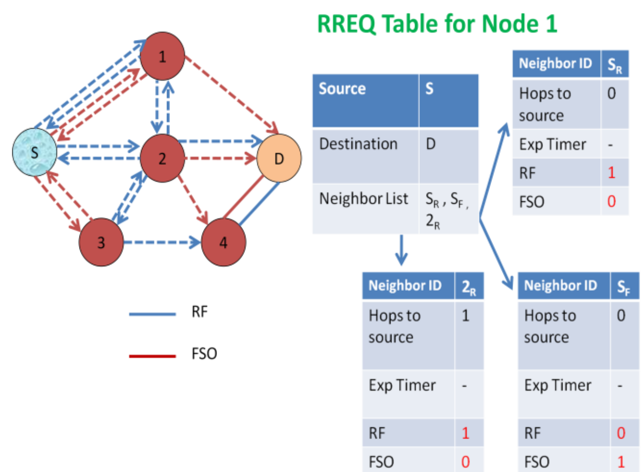


**Figure 7. RREQ Table for Node 1 (Stage 2)**

In our topology, destination receives the first RREQ from node 1 and generates a RREP to node 1 first. Upon receiving RREP packet from the destination, node 1 identifies the neighbor in the RREQ table via which the path to the source is the shortest and forwards the RREP to that neighbor as shown in Figure 9.

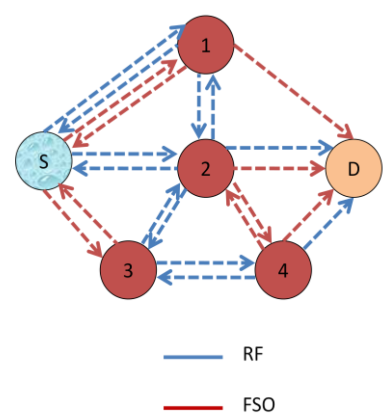


**Figure 8. Destination Receiving all RREQs**

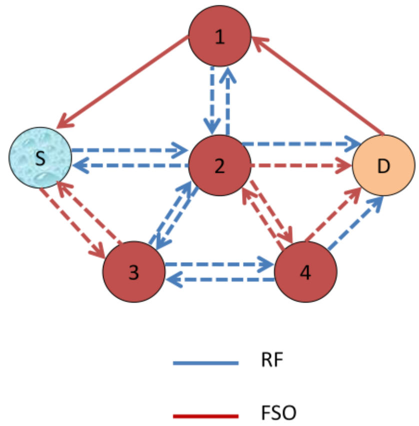


**Figure 9. RREP Reaching Source Node S**

A forward path is setup during the generation of the RREP message. After the forward path is established from the source node to the destination, the source starts sending data packets. The forward path is set up according to Figure 10.

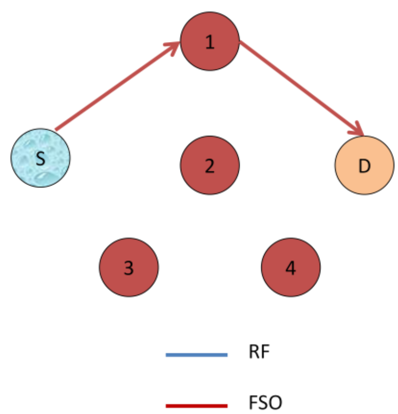


**Figure 10. Route Reply (RREP) for AODVH**

We consider multipath extension of our proposed protocol to reduce the percentage of packet loss, average end-to-end delay and to improve overall performance. For multiple paths, the destination node replies to all route request messages it receives from the intermediate nodes. In our topology, to achieve node disjointness, after forwarding the first RREP from node 1 to the source, the entry for node 1 is deleted from the RREQ table. After replying to the first RREQ message, destination sends RREP for all subsequent RREQ messages. During the generation of the RREP messages, forward paths are setup from intermediate nodes towards the destination. When all the RREP packets reach the source S, we have multiple paths to send data from source to destination D, with the first path being the primary one as shown in Figure 11.

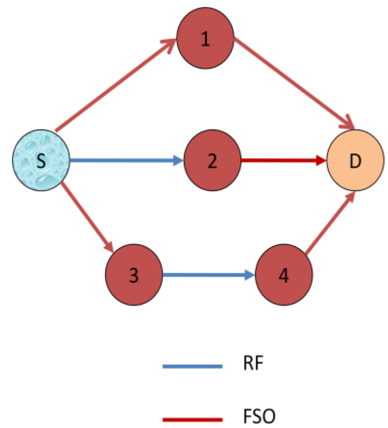


**Figure 11. Forward Path Setup from Source S**

## V. Performance Evaluation

### *A. Simulation Setup*

We have simulated our proposed protocol (AODVH) using Network Simulator (ns-2) [22]. Our objective is to evaluate the effectiveness of AODVH relative to AODV, especially when route failures occur due to mobility. We also evaluate the effectiveness of "FSO only" paths and "Hybrid" paths of AODVH over "RF only" paths of AODV in terms of throughput.

The Monarch research group in Carnegie Mellon University (CMU) added extra features in ns-2 to support simulation of multi-hop wireless networks including physical, data link and MAC layers [23]. Ns-2 has been used for evaluating the performance of many other AODV-variants proposed in the literature [23, 24]. The radio model characteristics are similar to a commercial radio interface, like the 914MHz Lucent WaveLAN DSSS radio interface. It is a shared-media radio with a nominal bit-rate of 2Mbps and radio range of 250 m. For Free Space Optical, we used the FSO characteristics model used at University of Nevada (Reno) [15]. Hybrid nodes were implemented with double interfaces consisting of FSO and RF links. The various simulation parameters are shown in Table 1.

**Table 1. Simulation Parameters**

| Parameter | Value |
|---|---|
| Network Size | 1000m x 1000m |
| Number of Nodes | 16 |
| Simulation Time | 100 sec |
| Mobility Model | Random Waypoint |
| Traffic Type | FTP |
| Channel 1 Type | FSO Wireless Channel |
| Channel 2 Type | Wireless Channel |
| Propagation Type1 | Free Space Optical |
| Propagation Type2 | Two Ray Ground |
| Interface Queue Type | Drop Tail/ PriQueue |
| Antenna Type1 | FSO Antenna |
| Antenna Type2 | Omni Antenna |
| Channel Capacity | 2 Mbps |
| Frequency for FSO link | 3.529e08 Hz |
| Node Speed | 5, 10, 15 and 20 m/s |
| Pause Time | 0, 2 and 3 sec |
| Node Placement | Random |
| Node Transmission Range | 250 m |

The results are averages of five simulations runs. Traffic pattern consists of FTP/TCP connection between a source and destination pair. The data packets have a fixed size of 1000 bytes in all the experiments. The random way point mobility model was used to simulate node movements [23]. We generated different random mobility scenarios using different node speeds. The maximum number of multipath routes was set to three, which has been shown to be an optimal number for multipath routing [25, 26].

### *B. Results*

We consider the following performance metrics to evaluate the performance of AODVH:

- Packet Loss
- Average End-to-End Delay
- Route Discovery Frequency
- Packet Delivery Ratio
- Throughput

**Packet Loss**: Figure 12 shows the percentage of data packets that are dropped either at the source or at the intermediate nodes with varying node mobility for AODVH and AODV. For AODVH, “FSO only” paths were used. An intermediate node drops a packet when it does not have a route to forward the packet. A source drops a packet if it fails to get a valid route after sending several Route Requests (RREQs) to get Route Reply (RREP) from the destination [2]. In our scenario involving multipath, the source always has a route to the destination; hence packet drops usually occur at the intermediate nodes. As the nodes are placed randomly, the number of nodes that a connection traverses varies between connections. The random way point mobility model is used to generate movement among the nodes where the speed and direction are all chosen randomly and independently of other nodes. The nodes in this scenario move along a zigzag path that consists of straight lines from one point to another way point where each point is chosen by uniform distribution [23].

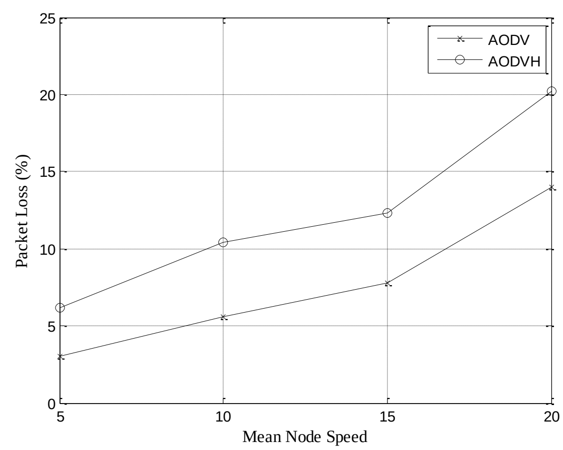


**Figure 12. Packet Loss with Varying Mobility**

With low node mobility, AODVH performs significantly better than AODV (50% less packet loss). The packet drops percentage for both protocols increase with increase of mean node speed. But AODVH still drops fewer packets compared to AODV at higher node speed (30% less packets when node speed is 20 m/s). This is because of the availability of alternate paths that are used in AODVH when a path breaks. AODV, on the other hand has to initiate a new route request when the only path breaks. As we see, the packet loss starts to increase for both the protocols at higher node speed which limits the performance of AODVH because the alternate paths fail more frequently due to movement.

**Average End-to-End Delay**: We define end-to-end delay as the sum of all possible delays encountered by a packet between a source and destination pair. The delays include data transmission, retransmission, buffering during the route discovery period, delays at the MAC layer, propagation time, etc [27]. We averaged the delay for all packets going from source node to the destination node, and compared the results of AODVH with AODV in Figure 13.

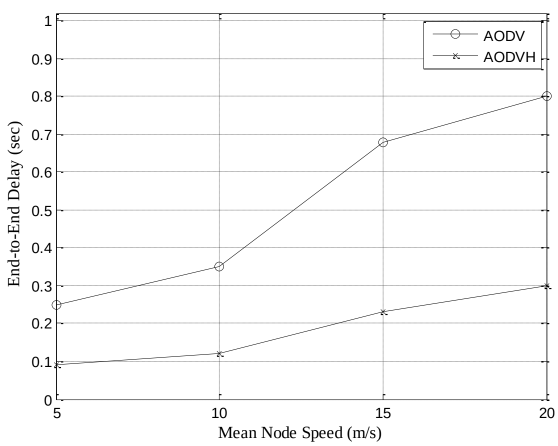


**Figure 13. End-to-End Delay with Mobility**

AODVH achieves 64% reduction in end-to-end delay when compared to AODV. The regular maintenance of "FSO only" paths in AODVH gives increased availability of valid alternate paths and decreased time to transmit data when the primary path breaks.

**Route Discovery Frequency**: We calculate the route discovery frequency by calculating the number of route requests generated by the source per second [2]. In a high mobility scenario, the route discovery frequency increases due to frequent failing of the routes. Figure 14 compares the number of route requests initiated for different node mobility scenarios for AODVH and AODV.

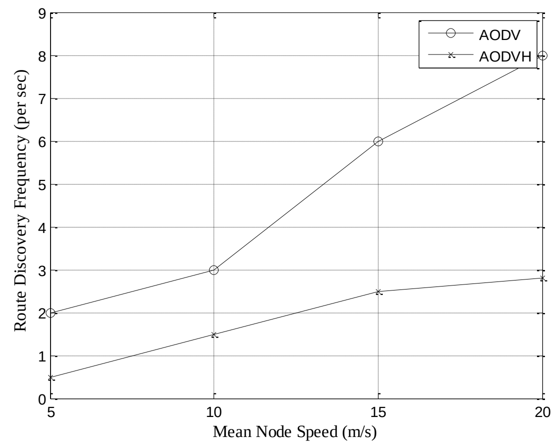


**Figure 14. Route Discovery with Mobility**

AODV has a higher number of route requests due to the availability of a single path. Every time the path breaks, a new route request has to be initiated. With increased mobility, the chances of breaking the single path increases, leading to a greater number of route requests. We examined the route requests for AODVH and found that the periodic maintenance of all paths reduces the use of invalid paths for routing, thereby preventing the source from initiating new route requests.

**Packet delivery ratio**: Packet delivery ratio is the ratio of data packets delivered at the destination to data packets transmitted by the source. At higher speeds, routes become invalid frequently and cause the packet delivery ratio to drop significantly.

We compared the packet delivery ratio for AODVH with AODV in Figure 15. It is seen that AODVH performs very well (97% packet delivered) when the node mobility is 5 m/s. In that case, AODV also performs very well (94% packet delivered). Because, in low mobility there remains a smaller chance of node failing, hence the packet delivery ratio is higher for unipath routing protocol like AODV. But with increased node mobility, the packet delivery ratio drops because of the frequent failing of the nodes in the topology. At higher node mobility (20 m/s), the performance of AODVH is reduced to 86% which is still better than AODV by 15%.

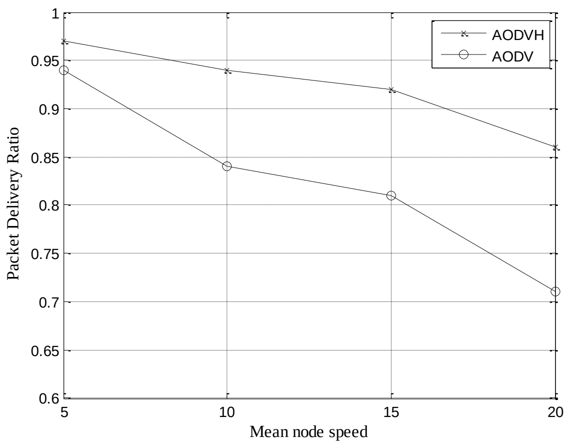


**Figure 15. Packet Delivery with Mobility**

**Throughput**: We calculated the amount of data received at the destination per second. We compared the throughput of AODVH with AODV for both "FSO only" and "Hybrid" paths.

Figure 17 shows throughput for AODVH for "FSO only" paths and throughput for AODV for RF only path. The throughput for "FSO only" path for AODVH is much higher (75% more) than the throughput for RF paths for AODV because of the higher bandwidth of FSO links.

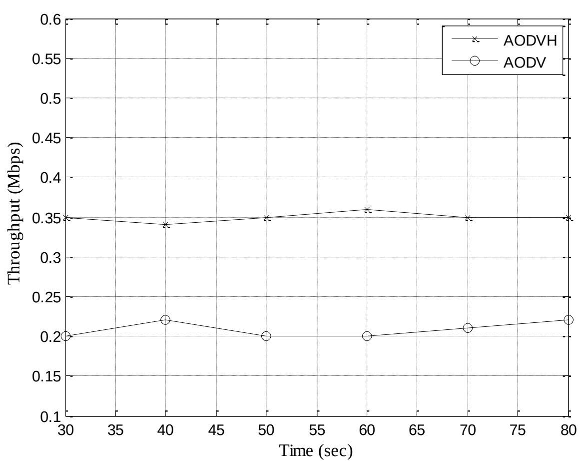


**Figure 17. Throughput vs. Time (FSO Only Path)**

Figure 18 shows throughput for AODVH for "Hybrid" paths and throughput for AODV for RF only paths. The throughput for "Hybrid" path for AODVH is higher (75% more) than AODV when FSO is available, and same as AODV when only RF is available (from 50 to 60 sec). Due to the intermittent characteristics of FSO links, "Hybrid" paths are needed to maintain the optimum performance of AODVH.

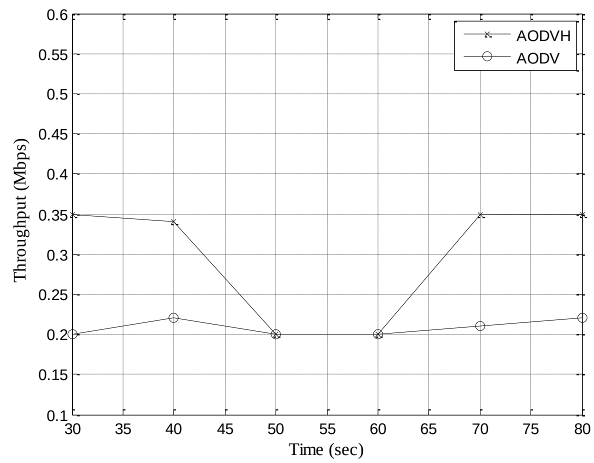


**Figure 18. Throughput vs. Time (Hybrid Path)**

From the results of this section, we conclude that AODVH performs significantly better compared to AODV in terms of packet loss, end-to-end delay, route discovery and throughput.

# VI. Conclusion

In this paper, we proposed and evaluated a novel multipath on-demand ad hoc routing protocol for Disaster Area Wireless Network which provides a rapidly deployable communications infrastructure for relief operations involving helicopters and ground workers. Mobility is an issue for DAWN. The proposed protocol, called AODVH, uses high bandwidth routes having "all FSO" links as the primary path and lower bandwidth hybrid routes of FSO and RF links as a backup path in the case of FSO link failures arising from weather conditions and optical misalignment.

Results validated that the multipath feature of AODVH minimized packet loss, end-to-end delay, routing overhead and route discovery and maximized packet delivery ratio. The advantages of using "Hybrid" paths with preference for "FSO only" paths include higher throughput in addition to those of multipath routing protocols.

In addition to disaster recovery, DAWN can be very useful in military and exploration missions, home area wireless networking, networking intelligent devices, sensors, mobile robots, and on-the-fly conference applications.

## References


[1] S. J. Lee and M. Gerla, "Split Multipath Routing with Maximally Disjoint Paths in Ad Hoc Networks," in *IEEE International Conference on Communications*, June 2001, pp. 3201-3205.

[2] Mahesh K. Marina and Samir R. Das, "Ad hoc on-demand multipath distance vector routing", *Wireless Communication and Mobile Computing*, John Wiley & Sons, Ltd., 2006,pp. 969-988.

[3] S. Vangala and H. Pishro-Nik, "A highly reliable FSO/RF communication system using efficient codes", in *IEEE GLOBCOM*, Washington, DC, November 2007, pp. 2232-2236.

[4] S. Adibi and S. Erfani, "A multipath routing survey for mobile ad hoc networks", in *IEEE CCNC*, 2006, pp. 984-988.

[5] S. Mueller, R. P. Tsang and D. Ghosal, "Multipath Routing in Mobile Ad Hoc Networks: Issues and Challenges" , Lecture Notes in Computer Science, 2004, pp. 209-234.

[6] S. Waharte and R. Boutaba, "Totally disjoint multipath routing in multihop wireless networks", in *IEEE ICC*, Istanbul, Turkey, July 2006, pp. 5576-5581.

[7] D. Johnson, Y. Hu and D. Maltz, "The Dynamic Source Routing Protocol (DSR) for Mobile Ad Hoc Networks for IPv4", RFC 4728, February 2007.

[8] T. Clausen and P. Jacquet, "Optimized Link State Routing Protocol", RFC 3626, October 2003.

[9] C. Perkins, E. Belding-Royer and S. Das, "Ad hoc On-Demand Distance Vector Routing", RFC 3561, July 2003.

[10] VD Park and MS Corson, "A highly adaptive distributed routing algorithm for mobile wireless networks", In *Proceedings of IEEE INFOCOM*, 1997.

[11] Z. Ye, S. V. Krishnamurthy and S. K. Tripathi, April 2003, "A framework for reliable routing in mobile ad hoc networks", in *IEEE INFOCOM*, San Francisco, CA, 1994, pp. 270-280.

[12] Y. Yuan, H. Chen and M. Jia, "An optimized ad-hoc on-demand multipath distance vector (aomdv) routing protocol", in *Asia-Pacific Conference on Communications*, Perth, Western Australia, October 2005, pp. 569-573.

[13] S. J. Lee and M Gerla, "AODV-BR: backup routing in ad hoc networks", in *Proceedings of IEEE Wireless Communications and Networking Conference (WCNC)*, 2000.

[14] A. Valera, WKG Seah and SV Rao, Cooperative packet caching and shortest multipath routing in mobile ad hoc networks, in *Proceedings of IEEE INFOCOM*, 2003.

[15] M. Bilgi and M. Yuksel, "Multi-element free-space-optical spherical structures with intermittent connectivity patterns", in *IEEE INFOCOM*, Phoenix, AZ, April 2008, pp. 270-280.

[16] Murat Yuksel, J. Akella, S. Kalyanaraman and P. Dutta, "Free Space-Optical Mobile Ad-Hoc Networks: Auto-Configurable Building Blocks", in *ACM/Springer Wirless Networks*, April 2009, vol. 15, no. 3, pp. 295-312.

[17] S. Gurumani, H. Moradi, H. H. Refai, M. Atiquzzaman and P. G. Lopresti, "Dynamic path reconfiguration among hybrid FSO/RF nodes", in *IEEE GLOBECOM.* New Orleans, LO, Dec 2008.

[18] H. Wu, B. Hamzeh and M. Kavehrad, "Availability of airborne hybrid FSO/RF links", in *Proceeding of the SPIE*, June 2005, vol. 5819, pp. 89-100.

[19] A. Kashyap, A. Rawat and M. Shayman, "Integrated Backup Topology Control and Routing of Obscured Traffic in hybrid FSO/RF Networks", in Proceedings of the IEEE GLOBECOM, Nov 2006, pp. 1-6.

[20] CE Perkins and P. Bhagwat, "Highly dynamic destination-sequenced distance-vector routing (DSDV) for mobile computers", In *Proceedings of ACM Sigcomm*, 1994.

[21] P. Yan, J. J. S. Jr., H. H. Refai and P. G Lopresti, "Enhancing mobile ad hoc networks with free-space optics", in *Optical Engineering*, August 2007, vol. 46, no. 8, pp. 1-7.

[22] K. Fall and K Varadhan, The ns Manual, 2002, http://www.isi.edu/nsnam/ns/ns-documentation.html

[23] J. Broch, D Moltz, D Johnson, Y-C Hu and J Jetcheva, "A performance comparison of multi-hop wireless ad hoc network routing protocols", in *Proceedings of IEEE/ACM MobiCom*, 1998.

[24] CE Perkins, EM Royer, SR Das and MK Marina, "Performance comparison of two on-demand routing protocols for ad hoc networks", in *IEEE Personal Communications*, 2001, pp. 16-28

[25] Asis Nasipuri, R Castaneda and SR Das, "Performance of multipath routing for on-demand protocols in mobile ad hoc networks", in *ACM/Kluwer Mobile Networks and Applications (MONET)*, 2001, pp. 339-349.

[26] Israel Cidon, Raphael Rom and Yuval Shavitt, "Analysis of multi-path routing", in *IEEE/ACM Transactions on Networking*, December 1999, vol. 7, no. 6, pp. 885-896.

[27] Perumal Sambasivam, Ashwin Murthy, and Elizabeth M. Belding-Royer, "Dynamically Adaptive Multipath Routing based on AODV", in *Proceedings of 3rd Annual Mediterranean Ad Hoc Networking*, 2004.