A Dual-path On-demand Routing Protocol for Tactical Wireless Networks

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Abstract— **Although multi-path routing protocols are more complicated to design than single-path based ones, they can be more resilient to route failures. Also, they can achieve a load balancing and hence lower end-to-end delay of transmitted messages in between a source and destination. Such advantages of multi-path routing can be significant in tactical wireless networks, where the messages transmitted are often time-critical and the topology are very unpredictable due to node mobility and link instability. In this paper, we propose a simplified multi-path routing (i.e., dual path) protocol for tactical wireless networks with multiple interfaces. Our dual-path routing protocol has an on-demand routing feature with route request/reply message exchange. We performed a simulation study using the OPNET simulator.**

***Keywords*—Tactical Wireless Networks, Dual-path Routing Protocol, Multi-interface, Multi-channel, On-demand Routing**

I. Introduction

With a multipath routing protocol, a source node can discover multiple paths towards a destination at once and utilize one of the-yet-discovered-path when the-first-used-path has experienced a failure. That is, an alternative route can be used immediately without the need of route re-discovery by the source, resulting in a lower end-to-end delay, less control message overhead by using alternative paths when having route failures, and higher throughput. Multi-path routing protocols are also known to be good at fault tolerance, load balancing, and even security in such a dynamic wireless networking environment [1].

Tactical wireless networks may experience many different types of environmental conditions, such as node mobility, multiple targets and destinations, deteriorated environments with obstacles, severe weather and jamming/interference attacks. These harsh environments of tactical networks cause frequent route failures and thus a frequent route discovery if a single-path routing protocol is utilized. In this paper, we argue that the multi-path routing approach can be a good solution to cope with these problems.

However, multi-path routing also has disadvantages, which are high complexity and high control message overhead to discover multiple paths, duplicated packet processing, and creation of longer paths [2]. High complexity and high control message overhead occur from allowing and processing duplicated/special control messages to discover multiple paths. This can decrease the entire network capacity. Our proposed scheme utilizes a dual-path feature and channel information to solve these problems. We verify that our protocol increases packet delivery ratio and reduces control message overhead.

In this paper, we propose a dual-path routing protocol, which is suitable for tactical wireless networks for reducing control message overhead for route discovery in multi-channel multi-interface environments. Channel information is used to reduce interferences and control message overhead.

The remainder of this paper is organized as follows. In Section II, we review the related works on multipath routing in wireless networks. We describe our dual-path on-demand routing protocol in Section III and describe how it finds multiple paths from a given source to a given destination. In Section IV, we discuss the simulation experiments performed with the proposed scheme and discuss the observed results. In section V, some conclusions and future works are discussed.

II. Related Works

In the recent years, several variants of multipath routing protocols tailored for wireless networks have been proposed. For instance, DSR (Dynamic Source Routing) [3] and TORA (Temporally-Ordered Routing Algorithm) [4] have the ability to find multiple paths. In DSR protocol, by using the information received from multiple route queries which might traverse distinct paths, the destination node can attempt to construct multiple node-disjoint paths. TORA builds and maintains multiple loop free paths using Directed Acyclic Graph (DAG) rooted from the destination.

AOMDV (Ad hoc On-demand Multipath Distance Vector) routing protocol is proposed to extend AODV for providing node-disjoint or link-disjoint multiple paths with 'advertised hop count' to guarantee loop-freedom [5]. It also has a particular property of flooding to achieve link-disjointness. This, in turn, guarantees lower delays but increases the number of delivered messages. AODVM (Ad hoc On-demand Distance Vector Multipath) is a multipath routing protocol that provides node disjoint paths [6]. The authors propose a new scheme for fast link breakage recovery and apply it to the AODV protocol. In this protocol, the message delivery ratio is increased at the expense of increased delay. However, the routing control overhead is high.

DYMOM (DYnamic Manet On-demand Multipath) [7] is a multipath routing algorithm based on DYMO routing protocol. In this protocol, Multiple RREPs are possible, since a new RREQ message may indicate a shorter path than the one currently used. Furthermore, all possible routes that may be established are at most one hop longer than the shortest path. However, the overload of this protocol is too heavy in environments where frequent route failures occur.

Traditionally, routing protocols in wireless networks are designed to find paths with minimum hop count. However, such routes may include slow or lossy links, leading to poor throughput. Instead, a routing protocol can select better paths by explicitly taking the quality of the wireless links into account. DSR, TORA, AOMDV, AODVM and DYMOM also use minimum hop count to discover routes. In this paper, we utilize a link quality routing metric to enhance throughput.

In recent years, MIMC (Multi Interface Multi Channel) feature is widely used for enhancing bandwidth and scalability (e.g. [8]-[10]). The five protocols mentioned above are not considered useful in MIMC (Multi Interface Multi Channel) environments because it was developed for single channel environment. When these protocols are utilized on tactical networks, high control overhead may occur in discovering multipath. This is because tactical wireless networks consist of multiple interfaces and multiple channels.

III. DUAL-PATH ON-DEMAND ROUTING PROTOCOL

We propose a dual-path on-demand routing protocol based on the AODV protocol to enable discovery of multiple paths from source to destination. We assume that if a node has multiple radios, they are tuned to different, non-interfering channels.

A. Route Selection with Airtime Cost

We utilize the *Airtime* cost as a link quality routing metric in our protocol that is specified in the 802.11s standard [11] to identify an efficient radio-aware path among all the candidate paths. The *Airtime* cost was developed to provide channel and interference aware path selection in wireless mesh networks. The *Airtime* cost reflects the amount of channel resources consumed by transmitting the frame over a particular link. This measure is approximate and designed for ease of implementation and interoperability. The *Airtime* cost for each link is calculated as:

$$C_a = \left[O + \frac{B_t}{r} \right] \frac{1}{1 - e_f} \tag{1}$$

Where O and B_t are constants listed in Table 1. The input parameters r and e_f are the data rate in Mb/s and the frame error rate for the test frame size is B_t respectively. The rate r represents the data rate at which a node would transmit a frame of standard size B_t based on current conditions, with its estimation dependent upon local implementation of rate adaptation. The frame error rate e_f is the probability that when a frame of standard size B_t is transmitted at the current transmission bit rate r, the frame is corrupted due to transmission error. This estimation is an optional choice for local implementation. Frame drops due to exceeding the TTL value should not be included in this estimate as they are not correlated with link performance. The path which has the smallest sum of *Airtime* cost is the best path.

Table 1. Airtime cost constants

Parameter	Recommended Value	Description
O	802.11a: 185 µs 802.11b/g: 699 µs	Channel access overhead
B_t	8192	Number of bits in test frame

Additionally, we utilize another factor of the route selection called *'channel triggered count (ctx)'* because one of the goals for this protocol is to find the route that consists of less interference on links. If each link on a node uses different channels, it can reduce interferences.

B. Route Discovery

The proposed routing protocol uses Route Request (RREQ) and Route Reply (RREP) messages defined in the AODV protocol for route discovery. Route Error (RERR) and Hello messages are also used for route maintenance. In MIMC environments, channel information of each link and number of triggered channels are included in RREQ and RREP messages to consider channel diversity. Also, to find faster and stable routes, we utilize link quality metric. To maintain the discovered routes, Hello messages are periodically transmitted. RERR message is transmitted when no alternative route exists and link failure is detected.

RREQ message contain channel information of each link on a path from source to destination. When a node broadcasts a RREQ message, the intermediate nodes add channel information of the backward link of the previous node. This channel information will be duplicated in RREP messages to verify a reverse path. Each intermediate node counts the number of channel trigger called *'channel triggered count (ctx)'*. Link quality field contains the value of the accumulated *Airtime* of each link on the route. When each node receives the RREQ message, the node updates its neighbor information and verifies it by comparing the RREQ ID. Then, the node broadcasts the RREQ message.

Figure 1 describes the example of route discovery steps in our protocol. For example, in initial phase as shown in Figure 1 (a) *Source A* broadcasts RREQ messages to *Destination I* to discover the dual-path. In case of node B, the node accumulates *Airtime* cost 120 and configures channel index as 1. Node D accumulates *Airtime* cost 100 and uses channel index 3. Node C accumulates *Airtime* cost 150 and configures channel index 2.

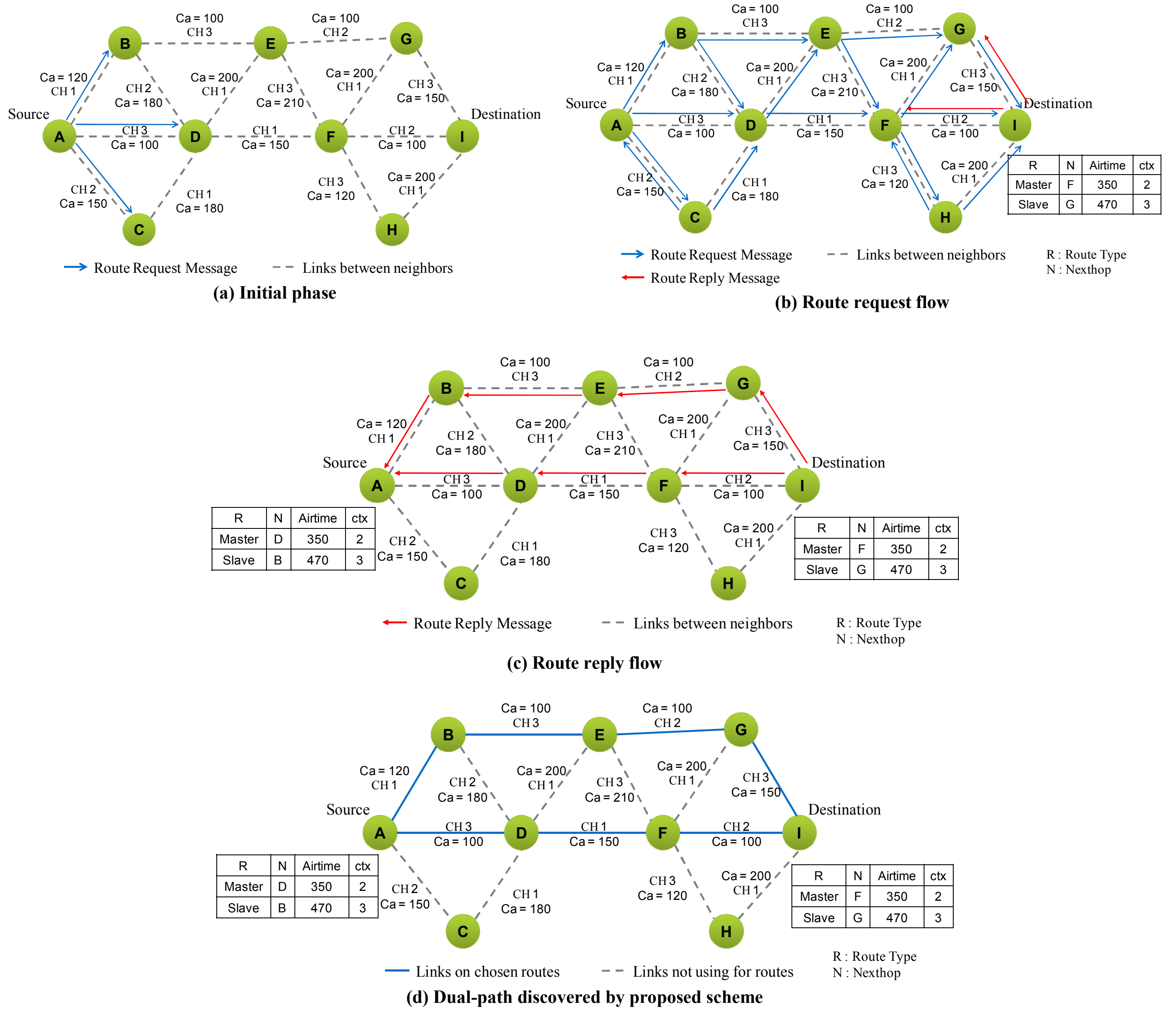

Figure 1. Example of route discovery steps

Afterwards, the nodes B, C, D forward RREQ messages to *Destination I*.

Similarly, as seen in Figure 1 (b), when node F receives a RREQ message from node D, it accumulates *Airtime* cost 150 (totally 250) and contains channel index 1. Node E also accumulates *Airtime* cost 100 (total of 220) and contains channel index 3 when a RREQ message is received from node B. Then, nodes E and F forward RREQ messages to *Destination I*.

Instead of discarding the duplicate RREQ messages, destination node of a RREQ message is required to record the information contained in RREQ messages with different channel using a table which we refer to as the RREQ seen table to make dual paths. For instance, when node D receives duplicated RREQ messages from node B and C, node D does not forward RREQ messages to destination and just updates neighbor entries and routing entries with accumulated *Airtime* cost and received channel index (as shown in Figure 1 (b)). The other nodes also follow the same procedure mentioned above.

For each received copy of RREQ messages, the destination node records its channel information of a link with a neighbor. The destination node compares link quality values with each received RREQ message. Then, it chooses the best two routes and sets the best route as primary route. Other route is set as the slave route on *'Route Type'* field in routing table. As shown in Figure 1 (c), *Destination I* receives RREQ messages from nodes F (with total accumulated *Airtime* cost 350 and channel index 2, route order is A-D-F-I), G (with total accumulated *Airtime* cost 470 and channel index 3, route order is A-B-E-G-I) and H (with total accumulated *Airtime* cost 570 and channel index 1, route order is A-D-F-H-I), then, node *I* records its channel information of a link with a neighbor and compares link quality values with each received RREQ message. Then, it chooses best two routes and sets the best one route (next hop is node F) as the primary route. The next best route (next hop is node G) is set as the slave route on *'Route Type'* field in routing table. After that, the node generates two RREP messages containing channel information duplicated from received RREQ messages. These RREP messages are sent back to the source via the path traversed by channel information contained in the messages, albeit in the reverse direction. The RREP messages are sent back to node F and G as seen in Figure 1 (c).

When each intermediate node on the reverse path receives an RREP message from one of its neighbors, it will find the correct path to destination with the least interference and adds a routing entry to its routing table to indicate the discovered route to the originator of the RREP message (the destination). The channel information inside the RREP packet can be utilized to find multiple paths by each route using different channels. When a node receives a RREP message, it identifies the neighbor by the channel information in the route table via which, the path to the source is the best path. When nodes F and G receive a RREP message, they forward the RREP message using its reverse path (F-D-A, G-E-B-A) as shown in Figure 1 (c).

Afterwards, it forwards the RREP message to the next hop node if it is not the destination node. If the receiving node is the final destination of the RREP, the new route is generated and updated. If a route already exists, the node compares receiving channel and link quality metric and chooses the better route as the master route and the other one to slave route. In Figure 1 (c), new route is generated when node A receives RREP messages. Path A-D-F-I is better route as the master route, so that the other path A-B-E-G-I is set as the slave route. When all the route discovery procedure is done, two routes will exist on the routing table. The discovered multiple routes are shown in Figure 1 (d).

When a node receives a Hello message, the node calculates the *Airtime* cost and records the receiving channel index. Then, it will update its route table entries and neighbor table entries of the changes in the channel. This message is transmitted periodically by each node to its neighbors to detect link failure. While a node detects link failures, the node switches the route type on master and slave routes, temporarily. Then, it sends a RERR message for repairing the detected link failure.

C. Route Switching

Furthermore, we add a route switching function because of condition changes. A node may switch master route to slave route or vice versa with following conditions.

1) Link failure is detected on master route. Master route is switched to the slave route temporarily until the master route recovers. If a new route is discovered but its link quality field value is higher than the quality of the temporary master route, it will instead be configured as the slave route.

2) When a periodic update makes the Slave route better than the Master route, the roles will be changed.

3) When the Master route is expired or becomes invalid, slave route is configured as the master route.

IV. PERFORMANCE EVALUATION

We compare the simulation results with AODV and our proposed dual-path on-demand routing protocol. We summarize the main findings of the comparison at the end of this section. The OPNET [12] simulation tool version 14.5 is used to evaluate and compare the performance of our protocol and AODV.

A. Simulation Environments

In this simulation, each vehicle node has 4 wireless interfaces. Three interfaces are used for inter-vehicular communications and the other interface is used for AP mode that communicates with mobile users. Vehicle nodes operate in the 802.11a mode (5 GHz) with 3 orthogonal channels for inter-vehicular mode. 802.11b model (2.4 GHz) is used for the mobile users and for the AP mode of vehicle nodes. The vehicle nodes are deployed 33 and mobile users are deployed 49. The simulation parameters are summarized in Table 2. Ten to twenty mobile users transmit packets to randomly selected sources across vehicle nodes in the simulation.

Table 2. Simulation environments

Parameters		Value
Simulation time		1000 sec
Hello message interval		1 sec
Route expiration time		3 sec
Data packet size		1024 bytes
Packet Generation interval		1 sec
Bandwidth	**802.11a**	54 Mbps
	802.11b	11 Mbps
Network size		25 km ×25 km
Topology		Random deployment
Mobility model		Random waypoint
Speed		5 m/s

The transmission range of tactical wireless networks is generally considered between 5~10km. IEEE 802.11 links are being used in long-distance settings that is up to several tens of kilometers [13]. Although 802.11 does not specify operation in long-distance settings, there are several vendor products available for such scenarios (e.g. Cisco, SmartBridges, iBridge, etc.), with proprietary MAC protocol modifications. There has been at least one research effort looking at protocol design for such long-distance networks.

We set transmission ranges in this simulation which IEEE 802.11a mode set as 10km and IEEE 802.11b mode set as 5km by simply changing transmission power of each node on OPNET simulator to consider the tactical wireless environment.

B. Performance Metrics

We use the following three metrics to compare the performance of the protocols.

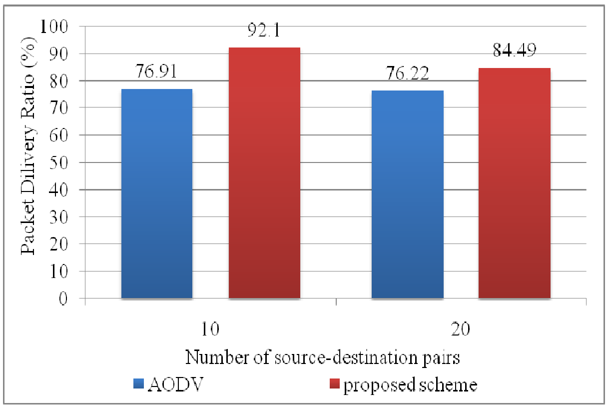

Figure 2. Packet Delivery Ratio (%)

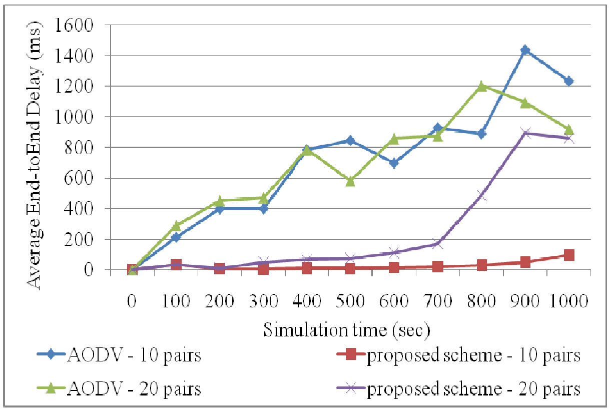

Figure 3. Average end-to-end delay (ms)

1) Packet delivery ratio: The packet delivery ratio is the ratio of the total number of received data packets by the destination to the total number of data packets sent by the source.

2) Average end-to-end delay of data packets: The average end-to-end delay is the transmission delay of data packets that are delivered successfully.

3) Routing overhead: The routing overhead is measured as the average number of control packets transmitted at each node during the simulation.

C. Simulation Results

The simulations are carried out 20 times and simulation results are calculated to average values of all the combined results.

Figure 2 shows the packet delivery ratio of the simulation. As we can see from the figure, the proposed scheme with feedback has better delivery ratio than the AODV because the protocol has the alternative route and switches to it when a link failure occurs or from some other conditions.

Figure 3 shows the simulation results of average end-to-end delay. It includes the queue delay in every node and the propagation delay from the source to the destination. As we can see from figure, compared with the single path protocol, it reduces end-to-end delay by utilizing route switching with an alternative route.

Figure 4 shows simulation result of routing overhead. Generally, high control message overhead can be expected because multiple RREQ and RREP messages are sent in multipath on-demand routing protocols. However, our protocol reduces control message overhead by using no multiple RREQ messages. In the figure, our protocol reduces the routing overhead more than 50% compared with AODV.

V. Conclusion and Future Work

In this paper, we propose a new dual-path on-demand routing protocol which is suitable for tactical wireless networks. We utilize link quality metrics *Airtime* cost and '*channel triggered count*' to select the least interfered routes. Simulation results from OPNET 14.5 show that the proposed

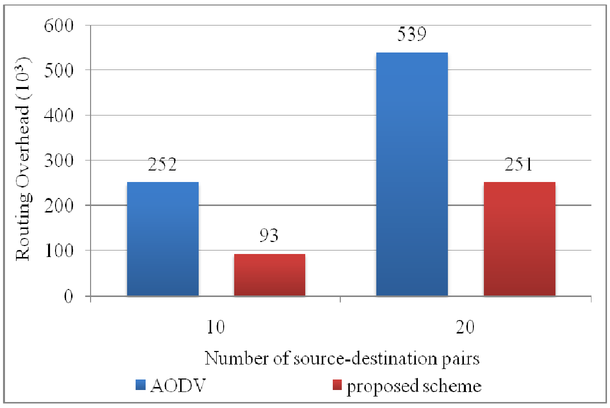

Figure 4. Routing overhead (10^3)

scheme has advantages over AODV. However, more comprehensive simulation study needs to be conducted to confirm the superiorities of this protocol, such as evaluating the performances in various mobility speeds. Different comparisons with other multipath protocols are also needed, to promote the performance of the proposed scheme.

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