A Routing Protocol for Utilizing Code Resources in Tactical Ad Hoc Networks with a Single Transceiver

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Abstract: A tactical ad hoc network is usually divided into several subnets by Code Division Multiple Access with frequency hopping sequences. In practice, the number of subnets needed in common tactical task is much lower than the theoretical networking capacity, which causes serious code resource waste. To make full use of idle code resources, we present a single-transceiver multi-channel routing protocol based on MCRP, named virtual dual-channel routing protocol (VDCRP). To overcome the disadvantages of serious overhead and high end-to-end delay of MCRP caused by employing multi-channel broadcast mechanism in multi-channel network environment, this proposed protocol provides a single-channel split-phase broadcast mechanism (SCSP) and a new metric called virtual dual-channel metric (VDCM). SCSP consists of control channel and data channel, which divides time frame into negotiation phase and data phase. In negotiation phase, all nodes exchange routing packets on the control channel. In data phase, all communication node pairs transmit and receive data packets on the data channel. We design the metric VDCM by considering both inter-flow interference and channel switching cost. Our simulation results show that compared to MCRP, VDCRP has higher resource utilization efficiency and lower ETE delay in multi-channel environment.

*Key-Words:*virtual dual-channel networking scheme; code division multiple access; broadcast mechanism; routing metric; split phase; network throughput; average end-to-end delay

1 Introduction

Wireless ad hoc networks that are widely deployed for VHF tactical communication today are mostly constructed by employing full network de-synchronization or synchronization. Compared to asynchronous network, synchronous network has many characteristics of network interoperability, large networking scale, high throughput, strong track interference resistance and so on [1]. Hence synchronous network is mainly used in large-scale tactical environment. A synchronous network is always divided into subnets by CDMA with FH sequences. In practice, the number of subnets needed in common tactical task is much lower than the theoretical networking capacity, which causes serious code resource waste. To improve code resource efficiency, we proposed a networking scheme based on virtual dual-channel structure in previous work. In this paper we mainly focus on multi-channel routing protocol as one of the key techniques of this networking scheme. Most of the multi-channel routing protocols are designed on the basis of traditional routing algorithms, which are divided into two types: proactive routing protocol [2,3,4,5] and reactive one[6,7,8,9,10,11,12,13].

In [2], Unghee Lee *et al.* proposed a routing protocol called DSDV-MC, which assigns one of available channels to the dedicated control channel and other channels to the data channel. This protocol allows each host equipped with two transceivers, so that a host can listen on the control and data channel concurrently. The routing protocol CA-OLSR proposed by Gong M. X. *et al.* combines routing protocol with channel assignment, which introduces the cross-layer concept on the basis of proactive routing protocol OLSR[3]. This protocol requires node maintain a routing table for recording the whole network topology information, while using one dedicated control channel for routing messages and one data channel for data transmission with multiple transceivers. Reghu A. *et al.* proposed a multi-transceiver multi-channel routing protocol MMCR [5], which selects routes that enhance bandwidth utilization while maximizing energy efficiency and minimizing end-to-end delay. This protocol forwards the packet using only the MPR nodes that a fraction of the all one-hop neighbors.

Each host also requires multiple transceivers. As mentioned previously, most past research is more suitable for the static network compared to the reactive protocol, so we mainly focus on the latter, which is more popular in the network with dynamic topology.

In [7], The reactive protocol MR-LQSR proposed by Draves R. *et al.* assigns multiple transceivers to each node, which the number of transceivers equals the available channels. Each node is fixed on an arbitrary channel for data transmission, while transmitting control messages on each transceiver by turn when broadcasting. This protocol uses a new metric called WCETT, which considers the interference between links at the same channel. However, this protocol will cause a sharp increase in the hardware costs as the number of available channels increases. There is another similar routing protocol called MMR proposed by Bo Yan *et al.*, which is also not fit for the multi-channel environment with a lot of idle channels [8].

Recently, one of the most popular routing protocols is to combine routing with channel assignment. Lu yang *et al.* proposed a joint channel assignment and cross-layer routing protocol (JCACR) based on AODV, in which a metric parameter named channel selection metric CSM is designed to evaluate channel assignment and to change the working channel dynamically when the channel is overloaded [9]. Yuan Feifei *et al.* also proposed a routing protocol CA-LQSR [12]. In this scheme, calculated transmission time (CTT) is proposed as the metric of channel assignment, which can reflect the real network environment and channel interference best, and enhanced weighted cumulative expected transmission time (EWCETT) is proposed as the routing metric, which preserves load balancing and bandwidth of links. Although these two protocols can provide higher resource utilization efficiency, however, they both need multiple transceivers.

Besides the simplest metric Hop Count, the first common metric is the expected transmission count (ETX) for multi-channel multi-hop networks, which considers both hop count and link quality except link capacity [14]. Based on ETX, Draves *et al.* proposed the weighted cumulative expected transmission time (WCETT) inheriting many of the properties of ETX, the limitation of which is that it does not capture inter-flow interference [15,16]. Then metric of interference and channel (MIC) proposed by Y. Yang *et al.* overcomes the limitation of WCETT by considering both inter-flow interference and intra-flow interference [17], however, has the disadvantage of routing around the edge of the topology due to the assumption that a link will always contend with neighboring nodes regardless of their current activity. A. P. Subramanian *et al.* proposed interference aware metric (iAWARE) for solving problems of MIC by using a more accurate interference model, which retains many of the properties of MIC [18].

In the VHF tactical network environment, the host should be more portability, more energy efficient, lower cost and so on. Hence, compared to multi-transceiver routing protocol, single transceiver is more suitable for virtual dual-channel networking scheme proposed before. For example, Multi-channel routing protocol (MCRP) proposed by Jungmin So *et al.* combines channel assignment to routing with only a single transceiver [6]. This protocol can solve *deafness problem* by assigning channels to flows instead of nodes, which is particularly suitable for the virtual dual-channel networking scheme. Hence, we focus on MCRP in this paper.

In MCRP, nodes may stay in different channels, which are selected from all the available channels according to certain rules. Thus, the multi-channel broadcast mechanism should transmit routing packets on all channels by switching channels quickly. As the number of idle channels increases, it will cause a serious control overhead and high ETE delay, and the node switching delay should be taken into consideration. The metric of MCRP is hop count, which is the traditional routing metric used in most of the common single-channel multi-hop wireless networks. This metric finds paths with the shortest number of hops. The primary advantage of this metric is simplicity, while the primary disadvantage is that it does not take link quality and link capacity into account. But both the link quality and link capacity are especially important for multi-channel network, because selecting paths should consider the interference of links. This can often result in paths which may cause some node congestion and consequently have poor quality performance.

In this paper, we propose a new routing protocol to use multiple channels with a single transceiver in ad hoc network. The proposed reactive routing protocol, Virtual Dual-Channel Routing Protocol (VDCRP), an extension of MCRP [6], provides not only an adaptive single-channel split-phase broadcast mechanism which can reduce the control overhead, but also a new metric which can provide a high quality and small hop-count path with estimating inter-flow interference and channel switch cost.

The rest of the paper is organized as follows. Section 2 presents principle of the networking scheme proposed in previous work. Section 3 presents the design of our single-transceiver multi-channel routing protocol VDCRP based on MCRP with single-channel split-phase broadcast mechanism and VDCM metric introduced. Simulation results are provided in section 4. Finally, Section 5 provides our concluding remarks.

2 Principle of Virtual Dual-Channel Networking Scheme

The dimensions of network resources are spatial, time, and frequency. Subnets always have different tactical task, the coverage area of which has characteristics such as adjacency, partial overlaid, and distance. It can be done that using other subnet resources by spatial reuse for improving resource efficiency. However, this paper only focuses on frequency and time dimension for simplicity. Here are these assumptions deployed: if the whole group-net frequency set are $\{f_0, f_1, f_2, \cdots f_{n-1}\}$, and number of the frequency points n, then the orthogonal-synchronous networking capacity is n which means the maximal number of subnets it can own with this frequency set. In this work the group net is divided into synchronous subnets by CDMA using multiple orthogonal FH sequences, the number of these sequences equals the number of frequency set. If the group net is divided into $m(m <<\neq n)$ subnets in a practical tactical activity, there will be $n-m$ idle sequences. So in this scheme the purpose is how to make fullest use of these idle sequences.

Idle code resources are illustrated in Fig. 1. For example, there are m subnets in Group 1, which occupies m sequences ($Seq.1 \sim Seq.m$). The other sequences $Seq.m+1 \sim Seq.n$ in Group 1 are unused, the frequency points of which control are idle code resources. In this scheme each subnet employs virtual dual-channel structure, which consists of only one dedicated control channel and multiple data channel. Control channel uses the FH sequence its subnet occupies, on which all nodes exchange various routing packets and some data packets for low-rate transmission task. Data channel employs the unused sequence by the approach of assigning sequences to flows, on which each node pair who have high-rate traffic can exchange data packets with occupying this sequence all the time till the transmission finished. Each host switches between control channel and data channel with only single transceiver.

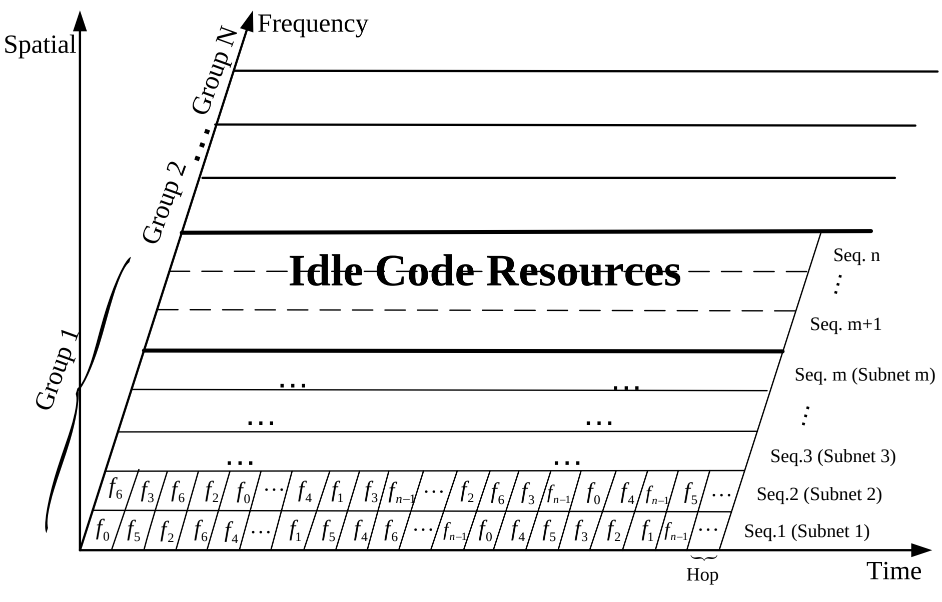

Fig. 1 Illustration: Idle Code Resources

3 Virtual Dual-Channel Routing Protocol based MCRP

3.1 The Metric VDCM

In multi-channel multi-hop wireless networks environment, most metrics of routing protocols are composed of the key components such as number of hops, link quality, link capacity, channel diversity and so on .In traditional multi-channel network, intra-flow interference of a path is relevant to channel diversity [15]. Because the channel assignment of VDCRP assigns a data channel to all nodes along the path, the channel diversity does not exist. Then intra-flow interference should not be the criteria to judge path performance. Because of inevitable path intersection phenomenon in our network, the switching nodes of a path will affect the transmission performance. Hence, the proposed virtual dual-channel metric (VDCM) considers hop count, inter-flow interference and channel switch cost. The VDCM metric of a path p is defined as follows:

$$VDCM(p) = (1-\alpha) * \sum_{i=1}^{n} iAWARE_i + \alpha * CSC \quad (1)$$

The $iAWARE_i$ component is the same as iAWARE [18]. The $iAWARE$ value of a link j is defined as follows:

$$iAWARE_j = \frac{ETT_j}{IR_j} \quad (2)$$

The ETT is the same as in WCETT[15] , which is deigned to describe the expected time to successfully transmit a packet for a link j. The value of ETT for a link j is defined as follows:

$$ETT = ETX \times \frac{S}{B} \quad (3)$$

S denotes the average packet size and B the link bandwidth. ETX is the expected transmission count, which is a measure of link and path quality by approaching of active probing.

The Interference Ratio value IR_j of a link j between node u and node v is defined as follows:

$$IR_j = \min(IR_j(u), IR_j(v)) \quad (4)$$

Finally, the IR_j value of a node v for a link j is defined as follows:

$$IR_j(v) = \frac{SINR_j(v)}{SNR_j(v)} \quad (5)$$

$SINR_j(v)$ is the Signal to Interference Noise Ratio and $SNR_j(v)$ the Signal to Noise Ratio of a node v for link j. Compared to $SNR_j(v)$, $SINR_j(v)$ considers the signal power received from interfering nodes.

The CSC component is designed to represent the channel switch cost of a path, which is defined as follows:

$$CSC = \sum_{i=0}^{N-1} CSC_i \quad (6)$$

N denotes the number of nodes of a path. The value of CSC_i is the channel switch cost of node i for a path, which is defined as follows:

$$CSC_i = \begin{cases} SC & if \quad NodeStatus_i = switching \\ 0 & else \end{cases} \quad (7)$$

In VDCRP each node is in one of following states such as free, lock, hard-lock, and switching. The node is only allowed to switch between two channels when its state is switching. The amount of switching nodes along a path can decide the transmission performance of this path. Switching cost (SC) of a node exists when it is switching node, which is defined as follows:

$$SC = \frac{SD}{PTT} \quad (8)$$

The value of Switching Delay (SD) is the channel switching delay for a single-transceiver, which is 80 μs in practical. The packet transmission time (PTT) is defined as follows:

$$PTT = \frac{PS}{DTR} \quad (9)$$

Packet Size (PS) is the average packet size, and Data Transmission Rate (DTR) is the rated channel bandwidth. $0 \le \alpha \le 1$ is a tunable parameter.

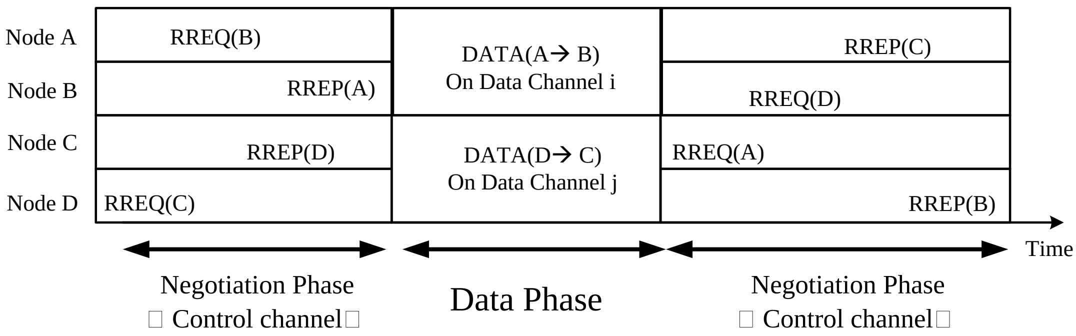

Fig. 2 Single-Channel Split-Phase Broadcast Mechanism

3.2 Single-Channel Split-Phase Broadcast Mechanism

The channel assignment method Split Phase divides frame into control phase and data phase, and it assigns channels to nodes in the control phase [19]. Based on Split Phase, this section propose a new broadcast mechanism called SCSP, which divides frame into negotiation phase and data phase, and divides channels into control channel and data channel. In the negotiation phase, all nodes of the subnet will switch its FH sequence to that sequence which control channel occupied. All the routing packets of the subnet will be exchanged on the control channel for route discovery, route maintenance, etc. When data phase comes, all nodes along the path between each communication node pair will switch their sequences to that sequence of data channel which the node pair belongs to. Then the data packet will be transmitted on each data channel until traffic ends or data phase ends.

For example, see in Fig. 2. In Negotiation Phase, node A sends a RREQ packet for finding a path to node B, node B sends a RREP to node A after receiving a RREQ from node A. After receiving RREP from node B, node A establishes a path to node B with assigning Data Channel i to all nodes along the path. In Data Phase, node A transmits data packets on the Data Channel i .When next Negotiation Phase comes, another route discovery begins.

3.3 Routing algorithm of VDCRP

VDCRP is designed based on AODV [20] as the same as MCRP, which consists of node state, route discovery, channel selection, packet forwarding and channel switching, force mechanism, and route maintenance. This section mainly focuses on node state, route discovery and forced mechanism. The descriptions of other components are ignored in this paper, because they only need a little modification for this scheme.

3.3.1 Node State

Each node is one of the four node states explained below. When a node joins the subnet at the beginning or has no high-speed traffic on data channel, it stays on control channel and switches to any data channel on data phase freely. This node is a free node. Once a node become a part of a path and switch to a data channel, it is a locked node. It is possible that two flows on different data channels can intersect at a node. In this case, the node where two flows intersect needs to switch between two data channels. This node is a switching node. A node is not allowed to switch between more than two data channels for reducing control overhead. Also, two consecutive switching nodes can't be on a data channel. Thus, the neighbors of a switching node on a data channel are hard-locked nodes, which can avoid *deafness* problems. A node must be in one of the four states. For example, see the scenario with three data channels in Fig. 3. Data Channel DC2 travels along the path S_2-e-f-D_2. Then node D_2 is a locked node, node e is a switching nodes, and node S_2, f are hard-locked nodes. Because no traffic passes through node c and node g, they are free nodes with staying on control channel.

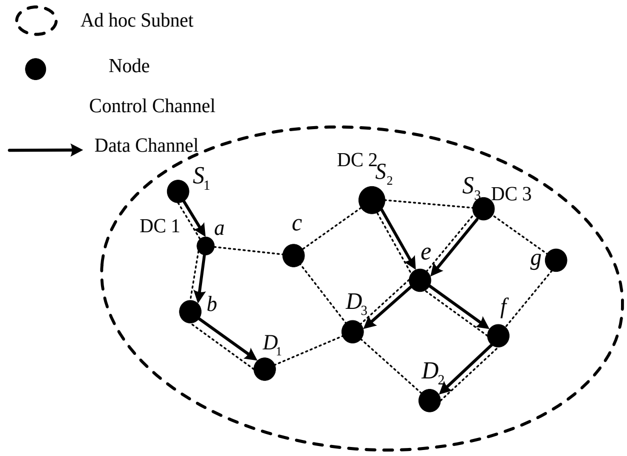

Fig. 3 Scenarios with three Data Channels

3.3.2 Route Discovery

Fig. 4 shows the route discovery of VDCRP. When negotiation phase comes, all nodes stay on control channel except some flows which have very urgent traffics. When a node has traffic to send, it starts a route discovery by broadcasting a RREQ packet with SCSP broadcast mechanism, which is similar to AODV. When an intermediate node receives a RREQ, it judges whether it was received before. If it was, the node choose the better RREQ which has a better path by the approach of calculating the metric VDCM. If not, the node creates a reverse route entry to source, and update RREQ with link information, channel table and flow table, then forwards RREQ to other nodes.

If the node received RREQ is destination, it starts channel selection mechanism. If it receives multiple RREQ within the given time, it chooses the best one by calculating VDCM. Then this node judges whether the route is feasible. If it is, the node assigns a data channel to this route and sends RREP to source node along the reverse route. If not, the node starts Forced Mechanism. If an intermediate node along the reverse path to source node receives the RREP, it updates the route entry and forward RREP. If the source node receives the RREP, it updates the route entry and ends the route discovery. When data phase comes, all nodes along this path between source and destination switch to the related data channel before source node sends data packets.

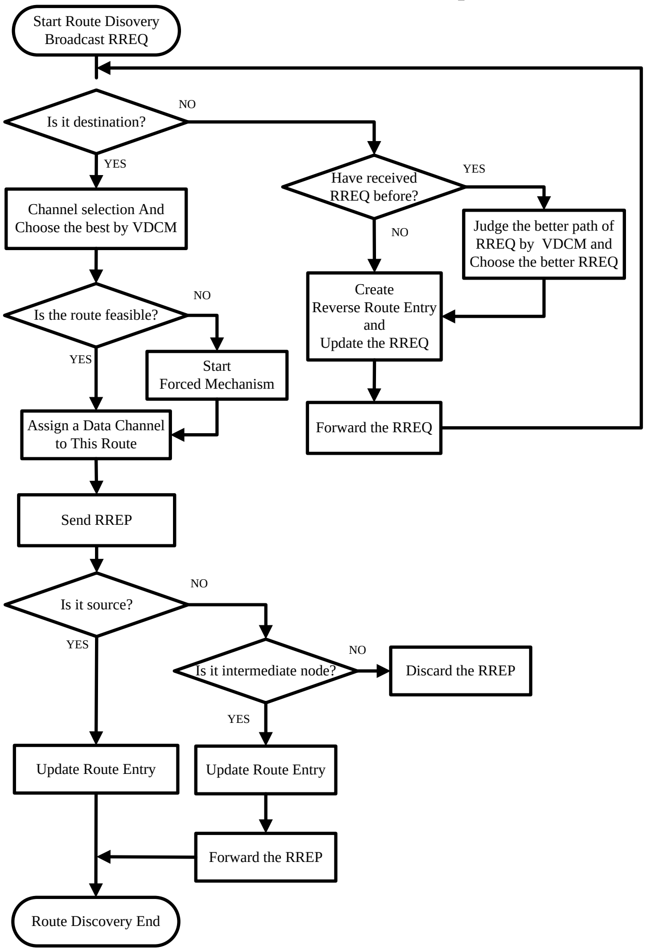

Fig. 4 Route Discovery of VDCRP

The route entry of VDCRP looks like the Fig. 5. In the route entry, all fields except *state*, *Data channel 1*, and *Data Channel 2* are also in MCRP. The *state* field indicates the node states. The *Data channel 1 and Data channel 2* fields indicates the local node is on. If the node is a switching node, it has two data channels.

dest	seqno	hops	nexthop	jflag
active	expire	state	Data channel 1	Data channel 2

Fig. 5 route entry of VDCRP

3.3.3 Force Mechanism

In route discovery, it is possible that the destination node receives one or more RREQ packets, but all potential routes are determined to be infeasible. Although there is a path between source and destination nodes, however, it will result in the route discovery failing to find a route if the destination drops all these routes. In this case, the destination will choose one path to reply RREP packets with the 'forced' flag set, which will change other routes along the path. This is called MCRP force mechanism. In this mechanism, all nodes can forward RREQ packets including hard-locked and switching nodes, which induce some routes infeasible because hard-locked or switching nodes will exist along the reverse route. This mechanism increases the route discovery time.

To solve this problem, the force mechanism of VDCRP consists of RREQ force mechanism and RREP force mechanism. In route discovery, hard-locked and switching nodes do not forward RREQ packets. The reverse route avoids hard-locked and switching nodes to reduce the probability of routing infeasible. If source node does not accept RREP packets from destination node, RREQ force mechanism starts up. In this mechanism, all nodes will participate to forward RREQ packets with 'forced' flag set. If all routes are still infeasible, RREP force mechanism starts up. RREP force mechanism is the same as MCRP force mechanism.

AREA	$40km \times 40km$
Number of Nodes	100
Frequency Range	$30 \sim 87.975MHz$
Number of Frequency set	256
Transmit Range	$5km$
FH Rate	$200hops/\sec$
Channel Width	$64Kbps$
Channel Switch Delay	$80\mu\sec$
Node Mobility Model	Random Waypoint
Packet Size	128 bits

Fig. 6 Parameter Settings of Simulation Experiment

4 Simulation and Results

The proposed VDCRP protocol was analyzed in OPNET simulations using IEEE 802.11 DCF with CBR sources. Fig. 6 shows the parameter settings of the simulation experiment. The first component of the metric VDCM considers inter-flow interference, which affects network throughput. While the other component CSC considers channel switch delay, which affects average end-to-end delay. Both throughput and delay are important metrics to ad hoc network, so α in VDCM is set to 0.5 for the simulation. The effect of α to VDCRP is not considered in this paper.

4.1 The Negotiation Phase Duration (NPD) and Data Phase Duration (DPD)

The duration of negotiation phase decides the route success ratio, which is related to network throughput. The duration of data phase decides the resource utilization efficiency. In the first set of simulations, there are 20 flows, and each flow has a data rate of 64Kbps. The duration of data phase DPD is set as 10secs for simplicity after considering resource utilization and network protocol standards. Fig. 7 shows the network throughput varying negotiation phase duration. There are 5, 10, 15 and 20 channels in Fig. 7. From Fig. 7, it is found that, all curves first increases then decreases, and a higher network throughput is derived between 1.5 sec and 2.5 sec. The reason is that, when NPD is too small, the nodes cannot make enough route discoveries to generate enough flows in the given data phase duration, which makes a lower throughput. When negotiation phase duration is too large, then negotiation phase is wasted, which decreases throughput and causes lower resource utilization efficiency. NPD is set as 2.5 sec later Due to five curses in Fig. 7.

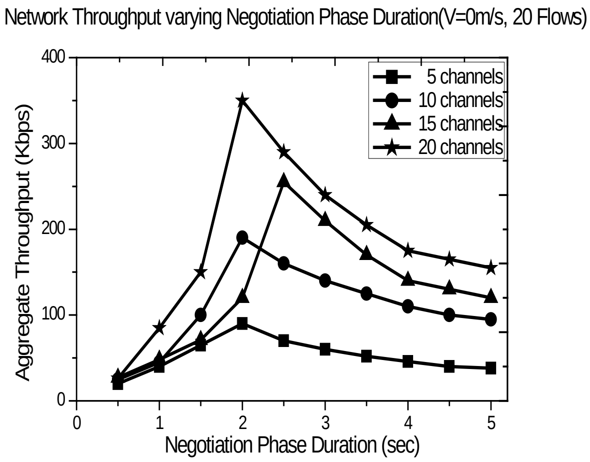

Fig. 7 Network Throughput varying Negotiation Phase Duration

4.2 Performance of Network Throughput

In the next set of simulation, we measured the network throughput varying the number of flows. The network has 21 channels, and each flow generates traffic at 64 Kbps. Fig. 8 shows network throughput varying number of flows. The channel bandwidth is quickly saturated, as the number of flows increases. The Fig. shows that AODV has a better throughput than MCRP and VDCRP when the number of flows is small than 5. This is because multi-channel scheme has a larger sacrifice of overhead for the benefit obtained than single-channel scheme when the number of flows is too small, which cannot make network saturated. When the number of flows is above 5, the network throughput of VDCRP and MCRP increase quickly, and the one of AODV decreases as a result of serious traffic overload. The network throughput of VDCRP and MCRP decrease when there are more than 20 flows, which is because of inter-flow interference caused by some of flows occupying the same channel. From Fig. 8, VDCRP can do a slightly better than MCRP because of smaller overhead VDCRP has.

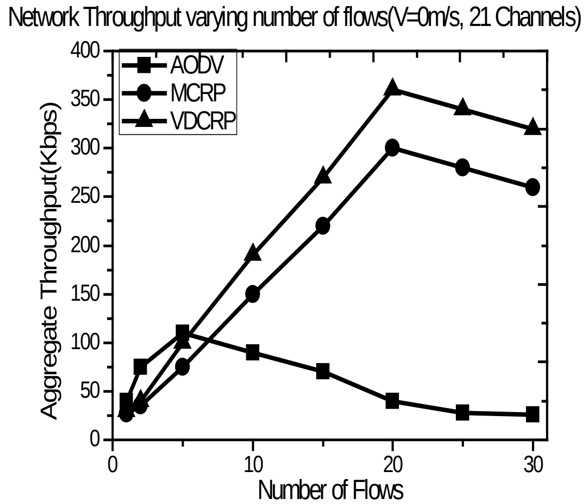

Fig. 8 Network Throughput varying Number of Flows

In this next simulation, it varied the rate of each flow from 512bps to 64Kbps. There are 21 channels in the area, and 10 flows having the same traffic generation rate. Fig. 9 shows the results. When the traffic load is small, both VDCRP and MCRP do not make a difference with multiple channels because the total traffic is less than the bandwidth of a single channel. With low load, AODV have a better performance due to the overhead in multi-channel protocol. As the flow rate increases, the throughput of AODV increases slowly due to the limit of a single channel. As the flow rate becomes large, the performance improvement of VDCRP over MCRP becomes more significant due to SCSP broadcast mechanism in VDCRP.

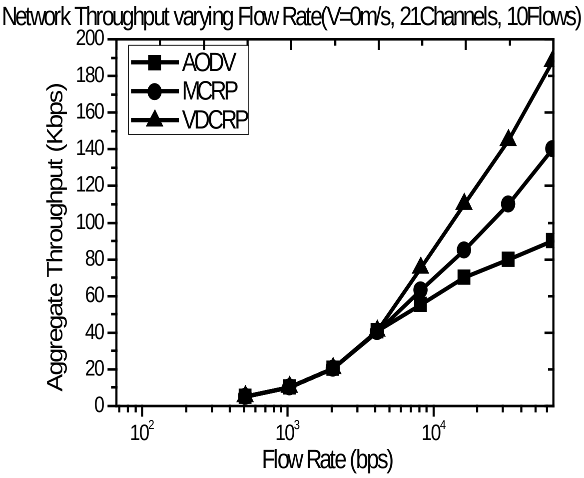

Fig. 9 Network Throughput varying Flow Rates

Then this simulation varied the number of channels from 2 to 10. There are 5 flows in this area, and each flow has a data rate of 64Kbps. The network throughput varying number of channels is shown in Fig. 10. When number of channels is less than 5, MCRP has a better performance than VDCRP as a result of an extra channel for control overhead transmission in VDCRP, and their network throughput increases quickly as number of channels increases. When the number is above 5, the network throughput of VDCRP stops at a constant value because the flows only use 5 channels, while the network throughput of MCRP have a large drop because the control overhead has to be broadcasted on more channels. So the conclusion is that the optimal number of channels used in MCRP is from 2 to 5, and VDCRP is suitable for a larger number of channels.

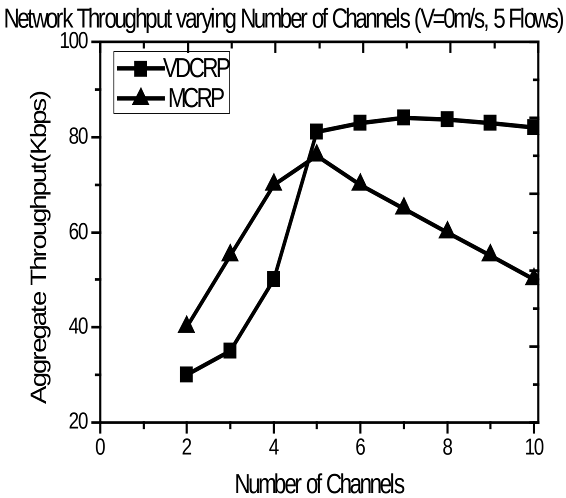

Fig. 10 Network Throughput varying Number of Channels

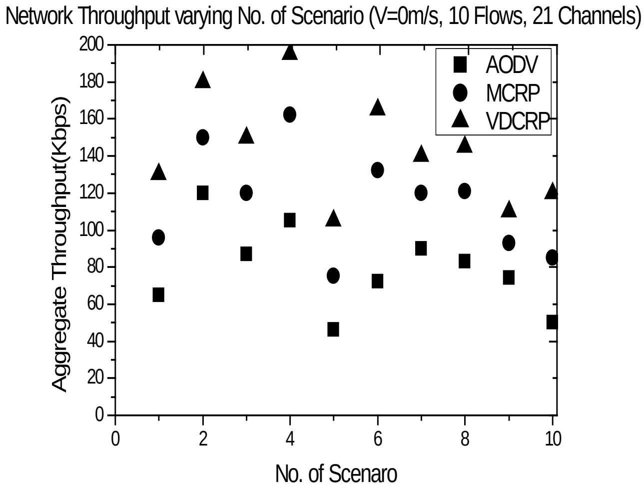

Fig. 11 Networking Throughput varying Scenarios

This simulation simulates the network throughput varying scenarios. In each scenario, there are 21 channels and 10 flows with the flow rate of 64Kbps. As shown in Fig. 11, in most of scenarios, VDCRP achieves a higher performance than MCRP and AODV. But in scenario 2 and 4, these protocols get a very high performance than other scenarios, which is because the network has a better topology and flows have a better path with few intersection nodes.

4.3 The Performance of VDCRP at Varying Velocity

Finally, this simulation measured the effect of node velocity to these protocols. The results are shown in Fig. 12. There are 21 channels and 10 flows in the network, and each flow has a data rate of 64Kbps. The node mobility is Random Waypoint mobility. From Fig. 12(a), the network throughput of VDCRP and MCRP has a rapid reduce as the node moves faster. As Fig. 12(b), (c), (d) are shown, the packet delivery fraction of VDCRP is less than other protocols because it needs more overhead for maintaining topology and route as the velocity increases, while the network overhead and average end-to-end packet delay of VDCRP is lower than MCRP but higher than AODV. The reason is that VDCRP does not need to switch to all channels for transmitting control packets, which reduces the network overhead and average packet delay.

5 Conclusion and Future work

In this paper, we proposed a new single-transceiver multi-channel routing protocol VDCRP based on

MCRP for improving code resource utilization efficiency, which is especially suitable for a network with a large amount of channels. We presented a new routing metric called VDCM that aids in finding paths that are better in terms of reduced inter-flow and channel switching cost. A new broadcast mechanism called SCSP was proposed to VDCRP, which is designed to reduce control overhead hugely based on MCRP. We also simulated the performance of VDCRP with OPNET. The simulation results showed superiority of our routing protocol. The proposed VDCRP exhibits significantly higher network throughput and smaller average end-to-end delay than MCRP when the node moves slowly with less control overhead in the environment of a large amount of channels.

There are several issues that are not addressed in this paper. First, as simulation shown in Fig. 12, the performance of VDCRP is degraded badly when the nodes move faster. Second, this protocol does not consider reducing intra-flow interference, which can affect link capacity and network throughput badly. These issues require a further research. To reduce the waste of code resource in practical, this proposed VDCRP has a significant prospective in tactical network with serious shortage resources.

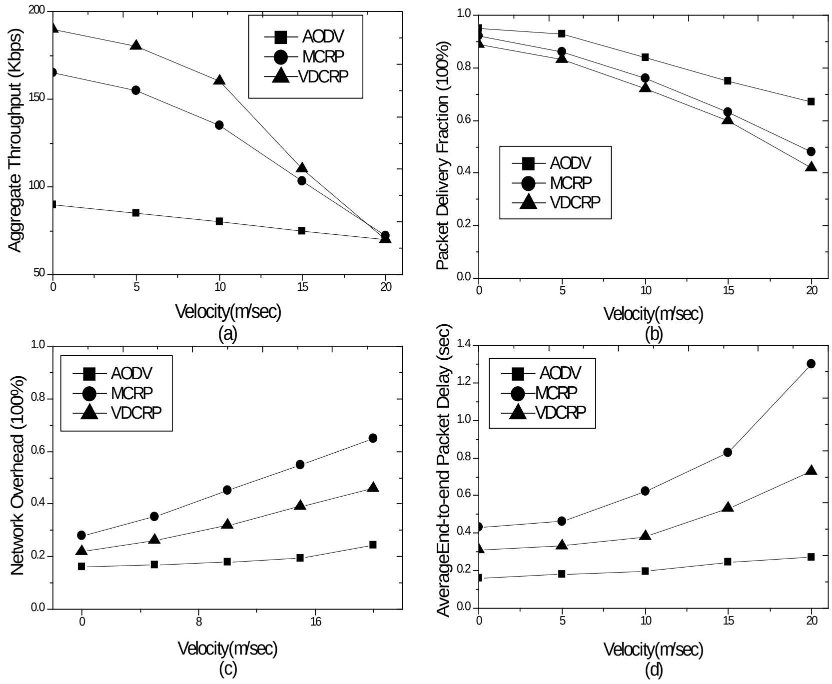

Fig. 12 Network Throughput, PDF, Network Overhead, Average ETE Delay varying Velocities, other parameters: 10 Flows, 21 Channels, 64Kbps Flow rate.

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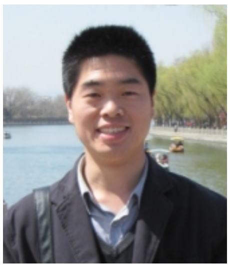

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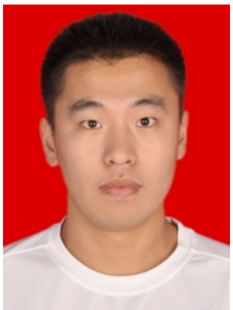

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