Resilient, Coding-Based Data Forwarding for Software Defined Mobile Tactical Networks

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***Abstract*—Software defined networking (SDN) increases the flexibility and efficiency of network management via a separation of control plane and data plane. However, bringing this flexibility and efficiency into mobile tactical networks is non-trivial due to the dynamics of wireless channel, the device mobility and network topology, which leads to substantial overhead on both control path and data path. In this work, we design a new architecture for software defined mobile tactical networks (SD-MTN) to address this challenge. In particular, we leverage the broadcast nature of wireless communication to design a coding-based data path for reliable, low-cost data forwarding. In the control plane, we leverage the global network view provided by the SDN controller to develop an efficient, centralized algorithm to compute and install proactive, resilient data forwarding decisions. In this way, data nodes forward redundant, coded traffic to proactively respond to transient node/link failures without waiting for the update from the controller or saturating the network. By supporting mobile networks to perform reliable, low-cost data traffic delivery and efficient, dynamic routing strategies adjustment simultaneously, this architecture significantly reduces the overhead of control path and data path in SD-MTN.**

I. Introduction

Software defined networking (SDN) increases the flexibility and efficiency of network management via a separation of control plane and data plane. This technique was initially designed for wired networks, such as data center networks, ISP networks and etc. Recently, academia, industry and military have started to explore the feasibility of introducing SDN into the context of mobile tactical networks (MTN) and redesigning the architecture of MTN. However, directly porting the SDN architecture to MTN is impractical due to (1) the dynamic nature of wireless communication, (2) the volatile mobility of communication devices, *e.g.*, vehicles, handheld devices carried by soldiers and etc., and (3) the frequent change of network topology. Specifically, to ensure the optimal handling of network traffic in response to the aforementioned dynamics, communication devices in the network need to send information about all the dynamics to the controller, which happens at a much higher frequency than that in the wired network, and the controller needs to recalculate and populate data forwarding decisions to all the devices in the networks. As a result, the control path overhead in the software defined MTN (SD-MTN) is substantially higher than traditional wired SDN. Hence, the fundamental challenge for designing such a SD-MTN architecture is: *how to minimize the traffic on the control path,* i.e., *the information exchange between communication devices and the controller, while still guaranteeing the optimal handling of network traffic at all communication devices?*

One strawman approach to address this challenge is to precompute data forwarding decisions for all possible network events and preinstall them on all devices. This approach, however, is infeasible for a few reasons. First, the number of possible network events, *e.g.*, link reliability change, (transient) link failures and etc., increases exponentially as the number of links in the network increases. Secondly, each device only has a partial view of the network. Without disseminating every event across the whole network, each device can only detect and react to network events that happen locally. This asynchronous forwarding decision update at different devices would cause loops, leading to the sub-optimal handling of network traffic. One may argue that disseminating every network event across the whole network can allow each device to react to non-local events. But it would introduce a much higher communication overhead between devices, compared with that of sending all the event information back to the controller. Furthermore, it still cannot address the drawback of asynchronous forwarding decision update at different devices.

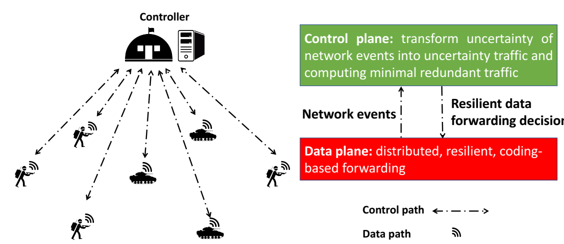


Fig. 1. The architecture of resilient, coding-based SD-MTN.

Overview. In this work, we tackle the aforementioned challenge by design a new architecture for SD-MTN, as shown in Figure 1. In particular, we design a novel coding-based data path. Leveraging the natural integration of network coding (NC) [1] and the broadcast nature of wireless communication, this new data path supports reliable, low-cost data forwarding in MTN. Different from the detect-and-react approach, we transform the uncertainty of network events to the uncertainty of traffic and proactively send *redundant traffic* for each data flow. In the control plane, we develop an efficient, centralized algorithm to compute the data forwarding decisions for each device to only send the *minimal* redundant traffic such that the resilient data delivery is guaranteed under a large number of network events without saturating the network. In this way, though each communication device still needs to send network event back to the controller, devices can still achieve the reliable data delivery without changing their data forwarding decisions. And the controller only needs to update the data forwarding decisions at each device when the proactively sent redundant traffic cannot guarantee the reliable delivery of data flows, which substantially reduces the control path traffic.

II. Design of Resilient, Coding-Based SD-MTN

Data plane: a coding-based data path. Network coding was first proposed for wired networks [1] and later extended to wireless networks due to the broadcast nature of wireless communication. Our coding-based data path uses random intra-flow network coding (RNC) to encode packets in batch with coefficient randomly chosen from the Galois Field with base 2^8. Figure 2 illustrates the process of NC-based data forwarding. The proposed coding-based data path uses the analytics framework developed in our previous study [2] to measure the expected transmission cost.

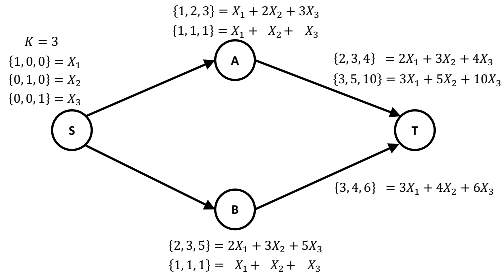


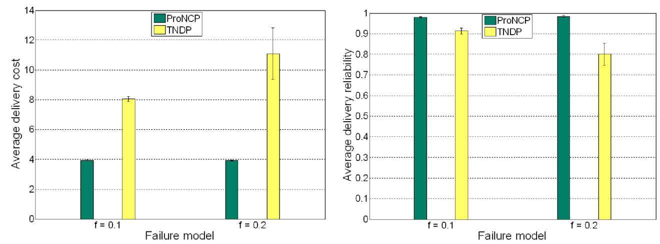
Fig. 2. An illustration of NC-based routing. The destination can decode a batch of K original packets as long as it receives K linearly independent coded packets.

Control plane: computing minimal redundant traffic for proactively, robust data forwarding. To minimize the information exchange between data plane and control plane while ensuring the optimal handling of network traffic at data plane, we transform the uncertainty of network events to the uncertainty of traffic and let each communication devices to proactively send coded redundant traffic for each data flow. To compute the minimal redundant traffic in response to different network events, we formally define the following problem: given a directed graph $G = (V, E)$ with one source S and one destination T, find two node-disjoint NC-based routing braids such that the total cost of delivering K linear independent coded packets to T along each braid is minimized. Note that at the current stage, we focus on single-node failure, one of the most representative network events in MTN. We are currently exploring how to compute the minimal redundant traffic to support resilient data delivery of data flow against arbitrary network events.

Different from the well-known minimal 2 node-disjoint path problem, we show that this new problem is NP-hard even in a simplified version through a reduction from the 2-partition problem. We also fix a mistake in the NP-hardness proof of the classic 2 integral network flow problem in [3]. With the complexity analysis, we develop an efficient, centralized heuristic algorithm to compute 2 node-disjoint routing braids for a given flow to proactively send redundant coded traffic. The algorithm first finds 2 node-disjoint paths with the minimal cost as a reference point. For each path, the algorithm then tries to attach unused nodes in the topology to build single optimal routing-braid using the optimal algorithm developed in our earlier studies [2]. In the end, it yields 2 node-disjoint routing braids, providing 1+1 proactive data forwarding decisions for the given flow.

III. Performance Evaluation

We perform preliminary evaluations on the 2 node-disjoint NC-based routing algorithm on the NetEye sensing and control testbed. The network is composed of 60 randomly chosen nodes, with 10 randomly selected as source nodes and 1 node chosen at the common destination node. This setting emulates a typical information convergecast scenario. We simulate the node failures in the network by setting a periodic timer of with random length at each intermediate nodes. Every time the timer fires, the node this timer is deployed has a probability of f to enter a transient failure status, i.e., not able to send or receive any packet. We comparatively study the performance of our 2 node-disjoint routing braids algorithm (ProNCP) and the classic 2 node-disjoint paths algorithm (TNDP) under different settings of f.



(a) Delivery cost under different node failure models.

(b) Reliability under different node failure models.

Fig. 3. Performance of ProNCP.

Results are summarized in Figure 3. We observe in Figure 3a) that the coding-based data path (ProNCP) is able to keep the delivery reliability close to 100% when f is set to be 0.1 and 0.2. On the contrary, The delivery reliability of regular data path (TNDP) degrades to 91% when $f = 0.1$ and drops to 80% when $f = 0.2$. This shows that ProNCP is able to provide resiliency against transient node failures for SD-MTN. Figure 3b) shows that even under the existence of transient node failures, the average transmission cost of ProNCP is kept stable at a very low level in both failure models.

IV. Conclusion and Future Work

In this paper we design a new architecture for software defined mobile tactical networks. We design a novel coding-based data path and an efficient algorithm in the control plane to making data forwarding decisions for each communication device to proactively send minimal redundant traffic towards destinations. This design minimizes the information exchange between data plane and control plane while still ensuring the optimal traffic handling on the data plane under the dynamic environment of MTN. The current algorithm is designed to proactively ensure data delivery under single-node failure events. As future work, we are exploring how to compute the minimal redundant traffic against arbitrary network events.

V. Acknowledgement

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