Routing optimization for network coding

Multi-flow route co-determination optimization with the use of delegated nodes

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***Abstract*—This paper presents ongoing results on the combination of ad-hoc network routing algorithms along with network coding to optimize the throughputs of multi-flows. After the presentation of the principle of the multi-flows route co-determination, the paper describes an optimization in terms of delegated nodes to extend the topologies the optimization may be applied to. Results on specific and randomized determination of topologies and flows are presented to estimate the gains expected when using these optimizations. Results on laptop demonstration follow.**

Keywords—Routing, throughput optimization, network coding, delegated nodes, Ad-hoc network

I. INTRODUCTION

The class of Mobile Ad-Hoc Network (MANET) is particularly prominent in military networks management, as these networks have to be deployable in harsh environments, with less infrastructure dependency.

The main characteristics of these networks are the self neighborhood detection, routing paths creation and the dynamic management of links/nodes.

The issues to be raised in terms of routing enhancement are manifold. One of these issues is the Quality of Service management, and in particular the routing based throughput optimization including resource allocation optimization. Algorithms have been proposed to optimize routing protocols for MANETs [1], [2], [3], [4]. Extensions [5], [6], [7], [8] and [9] integrate a quality of service management to these protocols. In [10] a multi-flow routes co-determination algorithm, in addition is proposed to these optimizations. This algorithm combines the (re)routing of traffic flows in ad-hoc networks with a throughput optimization technique called network coding. We present in this paper simulation results on the multi-flow routes co-determination, and on extensions to initial and terminal delegated nodes to extend the topology situations the algorithm may be applied to.

The paper is structured as follow. Section II presents principles on network coding and the novelty of the approach presented by the authors. In section III multi-flow route co determination protocol is reminded from [10]. In section IV is presented the optimization by the use of delegated nodes. Simulation and demonstration results are presented in section V. We conclude and present future works in section VI.

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II. NOVELTY WITH THE STATE OF THE ART

The work presented in this paper continues existing works on the optimization of MANET routing protocols with the use of network coding. After a reminder on the network coding principles and current state of the art, we present the novelty of our studies.

A. Network coding principles

The concept of *network coding* was first introduced for satellite communication networks in [11] and then fully developed in [12]. Its principle is described in Figure 1, part 1.A, applied on the butterfly topology. This figure presents two traffic flows, one from S_1 to D and F, the other one from S_2 to D and F. The principle is to code the two traffic flows with a common smaller one, using a coding function *Nc()* linear combination of the two flow packets, the traffic flow relevant from this flow being decoded by the use of the other flows already received. The figure shows the differences between the use of network coding and a standard (as [1], [2], [3], [4]) independent flow route allocation. The gain in terms of throughput and number of message sent between the two alternatives is of 1/3 (from 6 emission to 4, labeled from 1 to 6 and 1 to 4 in Figure 1, part 1.A), with means also a gain in radio resources and in power consumption in the relay nodes.

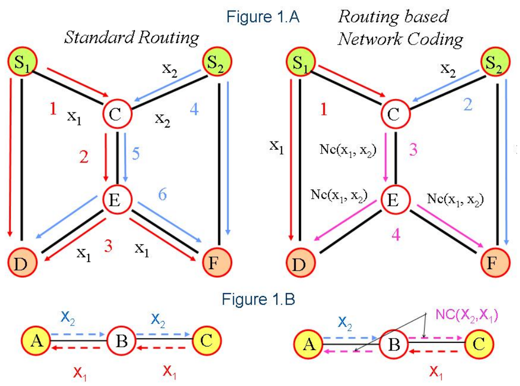

Figure 1. Network coding principle on the butterfly and 2 sides flows relay topology

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The Figure 1 (part 1.B) also presents the application of the network coding optimization on a 2 opposite sides flow relay topology. The optimization in terms of throughput is of $\frac{n}{2n+2}$ [13], with n as the number of relay nodes.

B. *Discussion on the novelty of the approach with the state of the art*

The use of network coding for the optimization of MANET is the object of several publications in recent years.

Authors of [13] proposed COPE, the first practical wireless coding system, which lay the foundations of the use of network coding optimization for MANET.

Patent [14] divulges a process that allows to combine routing and network coding. During the flow establishment, the process consists on counting the number of common links with the other flows, in enriching the reactive routing route requests RREQ. In a similar approach, authors of [15] propose the Distributed Coding-Aware Routing (DCAR) protocol. DCAR extends COPE by rising the limitation of two-hop region of coding opportunities optimization, and mixing the coding optimization procedures with flow establishment routing protocol. In these works there are no modification of existing flow routes. The route determination is processed flow by flow, without a global view of the flows.

Kano and all propose in [16] an extension of DCAR to modify existing flow path. In this extension initial nodes may decide existing flow routes switching from local node optimization for one given flow.

As the precedent work is based on local relay node detection of coding optimization, the particularity of the work proposed in this paper is to capture all the information needed to centralize the global information needed in the initial flow node to define the optimal flow routes, taking into account other flows routes to co-determine optimization opportunities.

In particular, in our algorithm, we propose to go one step further on the multi-flow routes co-determination. The novelty principle is in particular based on a symmetric flows relay nodes coding decision as explained in section III.B, including the information of the terminal to initial nodes sub paths in the paths information received.

In addition, We propose network coding optimization on topologies extension by the introduction of delegated nodes, described in section IV, and evaluated in section V.

III. MULTI-FLOW ROUTE CO-DETERMINATION ALGORITHM

The multi flow route co-determination algorithm aims at completing routing algorithm in the flooding and information recovery phases from the egress nodes of flows to be established. The detailed description of the algorithm may be found in [10]. In Figure 9, as laptops demonstration results, a sequence diagram of the algorithm message exchanges on 3 nodes bidirectional flows establishment is shown.

A. *Flooding phase:*

In a first step, during the flooding phase of the flow route establishment, the following information are stored on the nodes crossed. For each flow, the distance in number of steps to the initial node, and the precedent node in the path. The links are considered as bidirectional and stable during the traffic establishment. In the following figure are presented the results of this phase on a S1 to D and F for the flow X_1, and the S2 to D and F for the flow X_2. A simple bounded Dijkstra algorithm may be used to implement this phase. This phase may be applied at traffic setup, or by polling after traffic establishment to optimize the global traffic workload with new independent flows establishment.

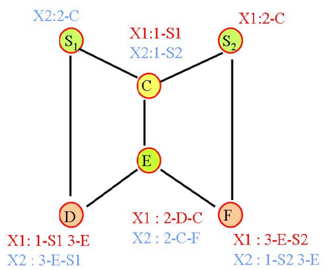

Figure 2. Information memorized during the flooding phase

B. *Information recovery phase:*

In a second step the egress nodes send information to the ingress nodes to create the flow routes, catching in the relay nodes the information needed to define at the ingress node level if a network coding optimization with one other flow is applicable.

This step consists to send information on these flows, periodically from candidate egress nodes by sending specific messages. These messages, called `topo` messages contain (1) the list of the nodes of the path of relay nodes from egress to ingress nodes, (2) if one of these relay nodes was the initial node of flows (for S_1 – *resp.* S_2 - to have the knowledge of the path $S_2 \rightarrow F -$ *resp* $S_1 \rightarrow D -$ for the traffic X_2 –*resp.* X_1 -), (3) if two flows are bidirectional (as in Figure 1, part 1.B).

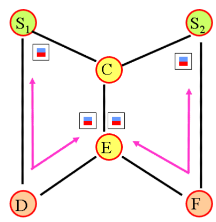

Figure 3. `Mtopo` messages sent to initial nodes

C. *Flow path setup phase:*

This phase consists on identifying the best route to send the flows at the initial node level, from all the `topo` messages received. The information of these messages contains in particular the information needed to know the traffics from other flows, to identify pivot nodes (which initiates and relay the network coding of flows), and if these pivot nodes are bidirectional.

In the flows initialization, the establishment messages set-up the paths to transmit the flows, and inform relay nodes of these path network coding is applied, identifying bidirectional ones, on which memorization, coding and decoding phases are applied. For example in Figure 1, part 1.B, the node B has to memorize packets from A and C, and to apply coding of these packets to send them, A and C have to memorize the packets sent, to decode the coded packets from B.

IV. Delegated nodes optimization

In the algorithm proposed in the previous section, we restrained the identification of:

- initial node candidates for the optimization algorithm as the nodes initiating two flows or nodes initial of a flow and terminal of one another;
- destination node candidates are nodes terminal of two flows and nodes initial of a flow and terminal of one another.

From a practical analysis of the topologies the algorithm may be applied to, it appears some topologies are very close to "canonical" ones and can't be candidate for network coding optimization although such optimization could be applied. For example the topology and flows depicted in Figure 4 shows a potential use of network coding optimization, but needs adaptations to extend the set of candidate topologies.

We propose to extend the set of the topologies with the definition of delegated nodes, on which the initial and final nodes may delegate to nodes which respect the initial and terminal candidate nodes prerequisites to apply the network coding optimization.

As a first definition of delegated nodes, we define as potential candidates the unique neighbor node of the initial and terminal nodes of a traffic (as S_{21} and F_1 in the example of Figure 4).

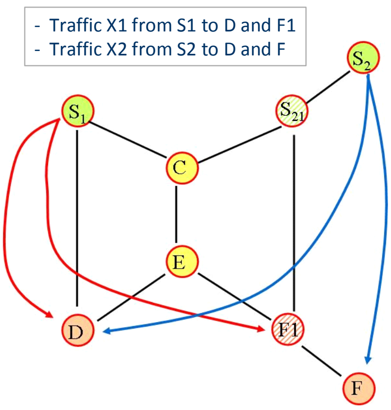

Figure 4. Network coding optimization with delegated nodes extension

V. Results

We implemented the network coding algorithm as a C++ program with input files defining the topology and two flows (being either 1to1 -*which means a traffic from 1 ingress node to 1 egress nodes*- or 1to2 -*which means a traffic from 1 ingress node to 2 egress nodes*-). The application computes the network coding application capabilities, corresponding paths and the theoretical percentage of gain in terms of throughput by number of packets exchanges between pair nodes.

A first section presents results on specific topologies and flows. A second result presents results on randomized topologies and flows. A last section present results on laptop experiments to estimate the signaling and control information overhead ratio with the throughput gain in a two bidirectional flows on three nodes.

A. Simulation results on specific topologies and flows

We first applied the algorithm on arbitrary defined topologies, some of them presented in Figure 5. As shown in Table I & II, the application on these specific topologies and flows give good results, with particularly good improvements with the use of the delegated nodes optimization, with a theoretical gain of 18.1% in terms of throughput.

Column (A) in Table I indicates capability to use the network coding algorithm without delegated nodes optimization. Column (B) indicates the capability to use the algorithm with the network coding algorithm with the delegated nodes optimization . Table II gives the percentage of topologies these optimizations are applicable to, and the global percentage of throughput gain. The throughput gain is computed as follows: $1-\frac{d_1+d_2-n}{d_1+d_2}$, with d_1 (resp. d_2) as the routing distance for the flow 1 (resp. 2), and n as the number of nodes network coding optimization is applied or combined data packets relayed.

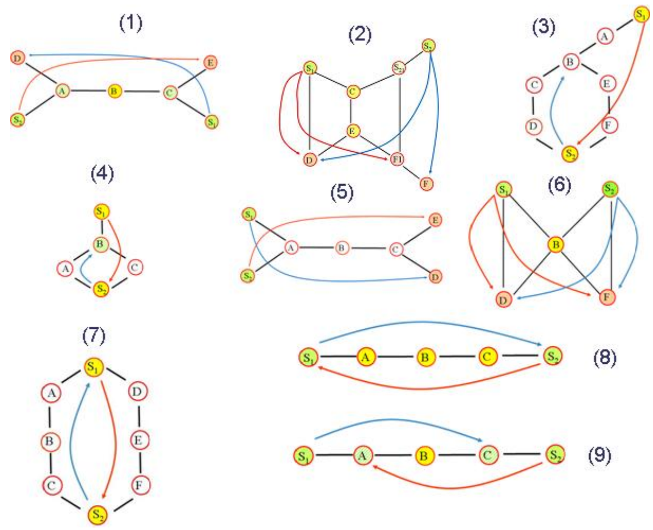

Figure 5. Different topologies and flows

TABLE I. OPTIMIZATIONS RESULTS

Topology and flows	**Table Column Head**		
	(A1)	***(B)***	***Throughput gain (%)***
(1)	NO	YES	12.5
(2)	NO	YES	25
(3)	NO	NO[1]	0
(4)	NO	YES	20
(5)	NO	NO	0
(6)	YES	-	25
(7)	YES	-	37.5
(8)	YES	-	37.5
(9)	NO	YES	16.6

TABLE II. OPTIMIZATIONS RESULTS

(1) to (9)	***(A)***	***(B)***
Algorithm applicable	33%	78%
Global gain	9.7%	18,1%

B. Simulation results on randomized topologies and flows

In a second step of the optimizations validation, we applied the optimizations on series of 200 samples of randomized topologies of 6 to 10 nodes, on a 4×4 grid, with the capability for the (x, y) located node to communicate to the $x \pm 1$ and/or $y \pm 1$ located nodes. For each of these sets of samples have been randomized 2 samples of traffic flows between nodes, with a distance of at least 2 hops. These 2 traffic flows being both with one or two destination nodes.

Figure 6 gives for the three kind of flows (two traffics 1to2, two traffics 1to1 and one traffic 1to2 and one traffic 1to1), on the randomized samples the traffics can be set (without optimizations), the percentage an optimization is applicable to with respect to standard routing protocols as [1], [2], [3] or [4]. In abscissa is indicated the number of nodes, and in ordinate the percentage of optimization applicability. We may see that this percentage decreases with the density of the network. The explanation is that there are less situations of flow paths crossing in a randomized draw of the samples.

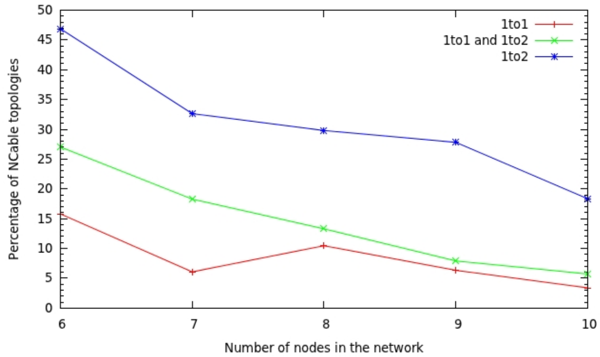

Figure 6. Percentage of topologies and flows the optimization is appliable to

Figure 7 presents, for all the situations where the traffic is possible (with or without optimization), the global gain of the network coding optimizations. In abscissa is indicated the number of nodes, and in ordinate is indicated the global percentage of gains with the use of network coding optimization with delegated nodes on the global samples the traffics were effective. For example, for the samples of randomized distributions of 6 nodes with two 1to2 traffics, network coding optimization is applicable in 46,9 %, with a final gain of 8.66% of gain, which means a global gain of 18.4% in the samples the optimization is applicable (quite similar to the figures in the case of specific topologies).

Figure 8 presents the gain of the delegated node optimization with respect to the initial network coding optimization algorithm proposed in section III. The results are given with respect to all the 1to1 and 1to2 combinations. We may see a real increase in the gains with the use of this optimization.

Although the definition of a delegated node seems to be restrictive, as the initial and terminal nodes need to have a unique neighbor, in the randomized selection of nodes we may state a real increase of the topology candidates for flows optimization. After a post analysis of the results, it appears that most of the time the optimization on bi-directional flows is the most applied, also with 2 1to2 flows situations.

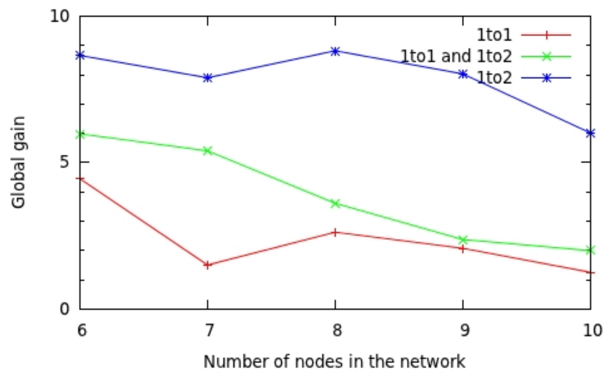

Figure 7. Global percentage of gain with the use of NC optimization

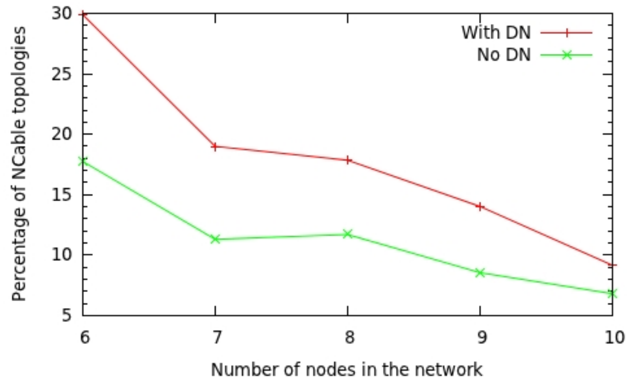

Figure 8. NC optimization by the use of delegated nodes

[1] May be optimized with an initial node 2-hops delegation, not evaluated in this paper (only 1 hop neighbour taken in account)

C. *Demonstration experiments results*

This section gives implementation details and results on first experiments on the protocol on a network of Wifi laptops demonstrator. A video of three laptops demonstration is available from the following link [17], with streaming webcam flows using Real Time Transport Protocol [18].

Figure 9 gives details on the protocol message exchanges between 3 nodes in the case of two flows establishment, from the node 1 to node 3 and from the node 3 to the node 1.

To manage, in a term of synchronisation, the network coding, we use for each node a messages queue of sent and received messages with a determined size as a constant (set to 10 in the experiments). When a relay receives a packets, it stores it into the queue, and wait for a packet from the other flow to code it with. If a packet is going to be stored into a full queue, before storing it, the older packet of the queue is repeated without coding to free a slot of the queue. This choice of implementation can induce a latency in the case of packet losses (mainly in dependent flows like *ping*), but it appeared to be the most efficient way of doing it in a term of throughput gain.

The link stability management is done by polling. Every initial node periodically sends a `Flooding` message to determine if the configuration didn't change. So there is always a mix between control packets and applicative packets.

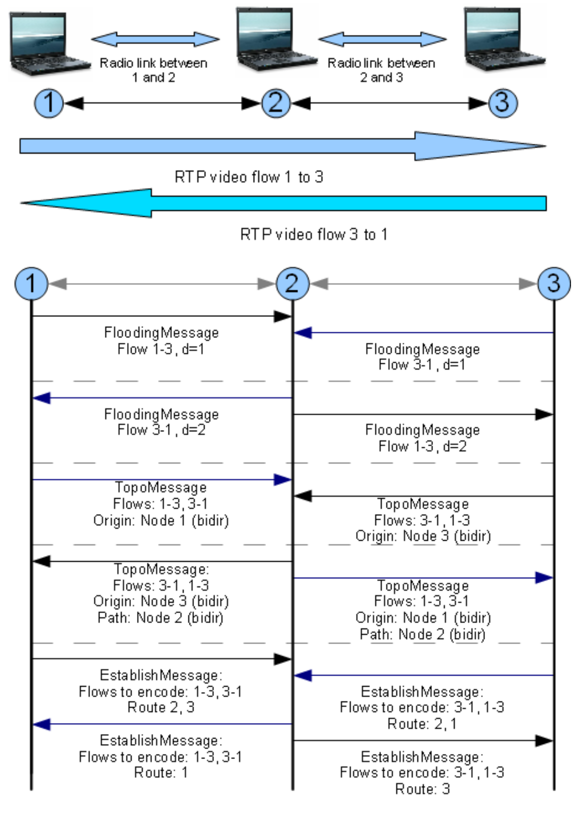

Figure 9. Sequence diagram of the message exchanges through the demonstrator

In this example, 20 IP packets of 1324 bytes are transmitted per second, which gives a global traffic of received and sent packets per second for the three nodes of 211840 bytes without optimization, and 185360 bytes with optimization.

The overhead in terms of IP packets header is of 40 bytes per packets (identifier of the 2 packet flows, size of the data, information in the case the packets have different size) which means an overhead of 3%.

Per polling period, set here as 4 seconds, the three nodes send 4 `flooding`, 4 `Topo` and 4 `Establish` messages of respective 54, 116, 64 bytes size, for a global throughput for these messages of 936 bytes every 4 seconds.

The added throughput per second in this example is of $936 \;\; 4$ (extra signaling) + 40×20 (overhead in packet headers sent by node 2) each second, which equals 1034 bytes, for a gain of 26480 bytes (ratio 3.9%).

The overhead in terms of messages exchanged is of 12 control messages sent any 4 seconds, when 640 data messages (in the case of no network optimization applied in node 2) are exchanged (ratio of 1.88%),.

As the control messages already exist in routing protocol (as RREQ, RREP messages for AODV [3]), and the size of the information added in the IP packet header may be optimized, the overheads are overestimated, and may be optimized in further studies. However, gains obtained from this experimentation justify the use of such protocol optimizations.

VI. Conclusion and Future Work

We first presented in this paper a proposal of network coding optimization on multi-flow route co-determination, reminded from further studies results [10]. Optimization on this initial algorithm follows to extend the set of topologies on which the multi-flow route co-determination is applicable, with the introduction of delegated nodes.

Results on an implementation of these optimizations are given, in a first time on a specific set of topologies and flows, and in a second time on randomized samples of topologies and flows. The results obtained are very promising, as they show good improvements on the throughputs in terms of number of data packets to be exchanged between pair nodes. The integration of the delegated nodes really improves the throughput gains.

But nevertheless, the delegated node definition is restrictive. Future work could lead to the definition of such protocol to valuate the gains of a more general definition of these delegated nodes.

Experiments on laptops integration of the optimization demonstrate a low overhead of extra signaling, and potential latencies induced to be tuned with respect to the quality of experience expected.

Section II presented the state of the art on other routing optimization with network coding. Most of them are based on a local distributed optimizations. We consider the study of a mix local/centralized approach might be promising and the object of further studies. Improvement of the route optimizations determination in the ingress nodes shall also be the object of future works.

The evaluation of the gains not on randomized topologies and flows, but on general missions real ground topologies is also a potential future work, along with the evaluation of the impact of mobility, variable stability links and self-healing procedures.

Finally, from the extended information provided to the initial nodes, we consider our solution offers potential improvements as coding optimization of more than two flows, or getting the coding decisions dependent of QoS criteria, as the link stability and available radio resource allocation capabilities on nodes.

VII. ACKNOWLEDGMENT

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