Energy Efficient Discovery of Neighbouring Nodes via Random Linear Network Coding

Riccardo Bassoli[1,2], Vahid Nazari Talooki[1], Hugo Marques[1,2], Jonathan Rodriguez[1], Rahim Tafazolli[2]

[1]Instituto de Telecomunicações, Aveiro, Portugal

[2]Centre for Communication Systems Research, Surrey, UK

$\{bassoli, vahid, hugo.marques, jonathan\}$@av.it.pt

$\{r.tafazolli\}$@surrey.ac.uk

Abstract

Managing and maintaining network connectivity in a mobile ad-hoc network (MANET) is known to consume bandwidth and energy at the mobile nodes. Traditional mechanisms require that stations periodically monitor the wireless channel, in order to determine available paths to route incoming packets. Aiming to alleviate the problem of energy consumption and high control overhead, this paper adopts a new approach to passive neighbourhood detection, based on Network Coding. Specifically, ad-hoc stations examine the coding vectors and subspaces of incoming network-coded packets to extract information about the subspaces spanned by these vectors, enabling them to passively discover new neighbours. The new discovery mechanism is incorporated into the well-known dynamic MANET on-demand (DYMO) ad-hoc routing protocol and the features of the combined scheme are discussed, towards assessing the potential advantages of the proposed approach, particularly with respect to energy efficiency.

Index Terms

Dynamic MANET On-demand, random linear Network Coding, passive neighbour discovery, energy efficiency.

I. Introduction

Mobile ad-hoc networks (MANET) are based on dynamic architectures in which stations cooperatively maintain network connectivity. To this end, each ad-hoc station needs to monitor the wireless connection with other ad-hoc stations within the range of wireless coverage.

---

*The research leading to these results has received funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under grant agreement 264759 (GREENET), from the European Community's Seventh Framework Programme [FP7/2007-2013] under grant agreement 285969 (CODELANCE) and from the Fundao para a Cincia e Tecnologia (PTDC/EEA-TEL/119228/2010 - SMARTVISION)

In MANET, communications between a source and a destination are usually supported by intermediate stations, which serve as relays to convey data. Thus, a network station participating in the communication process has to listen to the wireless channel in order to forward incoming packets.

Under such a complex scenario, maintenance and communication functions consume a significant portion of the energy resources of a mobile device, especially for intermediate nodes. As a result, the network lifetime is drastically reduced. Network Coding [1] is a promising technique that exploits the broadcast nature of the wireless channel to combine several input packets into several output packets, thus improving throughput and energy consumption. Recent studies have shown that the properties of network-coded packets can be used to determine network conditions, from finding the topology to locate bottlenecks and link failures.

The use of Network Coding for passive network monitoring was already discussed by a few research works that explored methodologies for passive network monitoring, based on random linear Network Coding (RLNC) in general multicast communication. These solutions can be classified in three categories:

- using information relevant to the subspaces spanned by the coding vectors in every node in the RLNC environment [2], [3];
- using information relevant to the transfer matrices, expressing the linear transformation from source to destination [4];
- using RLNC for failure detection [5].

Inspired by [2], this paper introduces a new approach that allows nodes to discover potential partners to establish wireless network links by passively exploiting the properties of network-coded packets. Hence, the energy and bandwidth consumed for the discovery of new network nodes can be reduced by significantly prolonging the network lifetime. Then, a dynamic MANET on-demand (DYMO) ad-hoc routing protocol that incorporates the new discovery mechanism is presented and evaluated through a theoretical framework.

The remainder of the paper is organized as follows: Section II discusses basic facts on RLNC and DYMO, providing the foundation for the proposed scheme, which is introduced and discussed in Section III. Finally, conclusions and future directions are presented in Section V.

A. Related Work

The definition Network Tomography for the family of problems of characterizing the internal properties of the network via some kind of measurements was firstly introduced in Vardi [6], because of the analogy between medical tomography and the operation of network characteristics discovery. The main contribution of this work was to provide a mathematical framework to study the problems of inferring network properties.

Next, after a decade, a promising technique in passive network monitoring [2], [3] exploits information relevant to the subspaces spanned by the coding vectors in every node in a RLNC environment. The proposed algorithm in [2] can identify the parent of every node and, with repetitive use, can detect the network topology. The structure of subspaces has also been exploited by [3], for peer-to-peer systems, in order to passively identify local bottlenecks, and to improve the formation of clusters. Sharma *et al.* [4] also exploits information relevant to RLNC for passive network monitoring, but through a different approach. This work proposes an algorithm (of exponential complexity) that can determine the topology of a (assumed error-free) network. The main idea behind this algorithm is that the transfer matrices (expressing the linear transformation from the sender to the receiver) corresponding to different networks are distinct with high probability. With respect to failure identification, Ho *et al.* [7] exploit RLNC to locate failure patterns across the network. The authors came up with results about the probability of identifying failure events. They also provided algorithms (of high complexity) to detect failures when the topology and coding coefficients are known a priori to the receiver. Passive network tomography for failure locations was also addressed by Yao *et al.* [5], for the case where all the coding coefficients are generated by the same random source (common randomness). This work points out that there is a relationship between graph properties of the network and linear algebraic properties of RLNC that can be exploited to detect random or adversarial errors and erasures. This approach has the advantage of keeping the measurement bandwidth low (transmission of coefficients) and the disadvantage of high computational complexity.

II. Background on RLNC and on routing for MANETs

We start by reviewing some basic facts on RLNC for wireless scenarios and on concepts related to ad hoc networks and the DYMO routing protocol.

A. Random Linear Network Coding in Wireless Networks

Let us consider a wireless network modelled as a hypergraph $\mathcal{H} = (N, E)$, where $|N|$ is the number of nodes and $|E|$ is the number of hyperedges with associated integer capacities (see Figure 1). A source s wants to communicate h packets to a set of sinks using linear Network Coding. In a wireless dynamic scenario the conditions of the network require to avoid centralised operations: hence, the most feasible solution is the application of random linear Network Coding (RLNC). In RLNC the nodes send random linear combination of received packets on the outgoing links. The packets are constituted by m symbols over the finite field $\mathbb{F}_q$. In order to be able to decode the information received, the sink that receives all

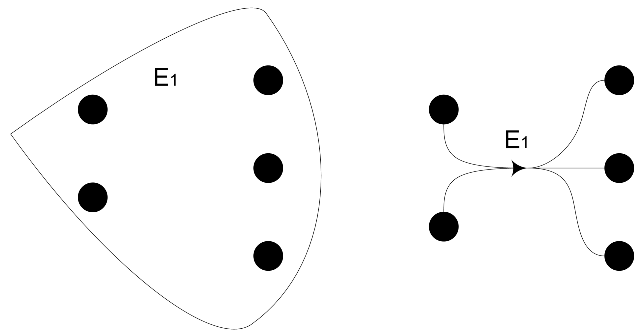

Fig. 1. Examples of hyperedges in an undirected hypergraph (left) and in a directed hypergraph (right).

the *h* linear combinations also needs to know the coefficients. Because of that, all the linearly combined packets have appended the coefficients in the header *coding vectors*.

The stream of packets sent by the sources are divided into blocks including packets of the same session: these blocks are called *generations*. There are two ways of designing and implementing Network Coding operations in practical protocols: *inter-session* and *intra-session Network Coding*. The former allows to combine packets without taking into account generations and the latter allows only combinations of packets belonging to the same session.

B. Ad hoc networks and Dynamic MANET On-demand

In the general case, a wireless ad hoc network is a wireless network, dynamic in nature, created by the cooperation of multiple wireless nodes; such network is known by the absence of an established infrastructure and from its independence of a central administration. If the nodes composing the network are mobile, this type network is also known as Mobile Ad Hoc Network (MANET). In MANETs each node operates both as a source, intermediate device or destination of a communication. When performing the functions of an intermediate node, mobile nodes act like a router and forward packets for other wireless nodes in the network that may not be within direct transmission range of each other. Routing protocols in MANET can be divided into three major groups [8], [9]:

- **Flat routing protocols**: where all nodes participating in routing adopt a flat addressing scheme and play an equal role.
  - *Flooding Protocol*: where every incoming packet is sent out on every other link by every router; easy to implement, but the algorithm generates a great number of redundant packets that can overwhelm a network.
  - *Proactive Protocols*: consistently attempt to find and maintain complete, up-to-date routes between all source-destination pairs regardless of the need of such routes; this approach require

periodic control messages to maintain routes up to date for each node.

  – *Reactive Protocols*: where routes are created by the request of a source node; data forwarding is accomplished either by source routing protocols or normal routing (hop-by-hop based).

- **Hierarchical routing protocols**: where the network is divided in groups (clusters) and each cluster has a cluster head; all administrative selection process will be dynamically performed and distributed – nodes have different responsibilities.
- **Mixed or Hybrid Protocols**: A combination of any of the previous types of protocols.

DYMO is an on-demand reactive routing protocol – currently defined in an IETF Internet-Draft [10]. DYMO was recently renamed by IETF to Ad Hoc On-demand Distance Vector version 2 (AODVv2) in its last version [11], since it was based on AODV protocol [12]. DYMO does not add extra features or extents the previous reactive protocols (AODV and Dynamic Source Routing (DSR)) [13] but simplifies them and still conserves the two main well known operations of reactive protocols: route discovery and route maintenance.

In route discovery phase, when a node needs a route to a destination host, it broadcast a ROUTE REQUEST (RREQ) message to its neighbours. The RREQ is flooded in the network until it reaches to destination or a node that has a route to the destination. Each intermediate node that forwards the RREQ (unlike AODV and more similar to DSR) add its address at the end of path – which is called *accumulated path* – creates a reverse route from itself to the source node and records it. Again in DYMO, if a destination receives several RREQ from the same source via different paths, it will reply all of them with different ROUTE REPLY (RREP). This way the source node can find several paths towards the destination. If an intermediate node discovers that any link on a route is broken, it will send a ROUTE ERROR (RERR) packet to inform the source. Every node who also receives this RERR will update its routing table. Each entry in the routing table consists of the following fields: Destination Address, Sequence Number, Hop Count, Next Hop Address, Next Hop Interface, Is Gateway, Prefix, Valid Timeout, and Delete Timeout [8].

III. Combining RLNC with DYMO: The scheme and its features

The proposed approach is inspired by the results described in [2] and [14], applied for passive network tomography with RLNC. These works allow inferring the network topology from the information collected by nodes about the subspaces spanned by the coding vectors. Our observation is that this information can contribute to passively detect neighbour nodes and new nodes of the network by avoiding high cost routing signalling. Moreover, the passive information helps the routing protocol to perform better and to be more energy efficient, since it now can use the collected list of neighbours (including new nodes joining the network).

The nodes of the network encode information packets belonging to the same generation (intra-session Network Coding) by choosing random coefficients over a finite field $\mathbb{F}_q$. The deploy of intra-session Network Coding guarantees that DYMO and RLNC do not interfere and effectively complement each other. Then, it is important to underline that the encoding operations do not involve DYMO control packets. Once the nodes of the network receive encoded packets from the neighbours, they collect information about the subspaces spanned by the coding vectors. Next, by processing this information they monitor the dimension of their subspace and calculate the intersections between subspaces. Thus, the quantities of interest in our model are:

- ID of the nodes;
- $\dim(W_i)$, the dimension of subspace W_i of a node i;
- $\dim(W_i \cap W_j)$, the dimension of the intersection between subspaces W_i and W_j referred to nodes i and all its neighbours j.

In particular, the dimension of the intersection of subspaces helps to update the relations of inclusion to estimate the list of the neighbours.

If a node is in idle state it is considered inactive and not part of the network. A node is detected and becomes part of the network once it sends the first packet.

Figure 2 depicts an example of how the passive information provided by RLNC is used to detect a new neighbour node, which is joining the network. First, the graph of the network at time t is drawn on the left of the Figure. Node A has transmitted two linear combinations of packets to both Node B and Node C. In particular, the subspaces W_A, W_B, W_C are respectively spanned by the coding vectors of packets $(1, 2, 3)$, $(1B, 2B)$ and $(1C, 2C)$. The image on the right of Figure 2 shows that a Node X joins the network by communicating with Node C at time $t + 1$. Then, the subspace W_C gets a new coding vector and, as a consequence, W_C is not a subset of either W_A or W_B. So, Node C can detect that he has a new neighbour and sends this information to its other neighbours. It is possible to see that, thanks to this framework, the control signals normally used to detect neighbours are translated into the processing of internal information at the nodes (the coding vectors stored in their memory). Moreover, it is also needed that the dimensions of the subspaces and the dimensions of the intersection of subspaces are stored by nodes. When Node C knows that there is a new Node X, it sends a request of its ID and provides it to the other nodes. Every time a packet is received the information about the subspaces has to be updated.

The environment for the proposed neighbour discovery via RLNC is a wireless network that has features

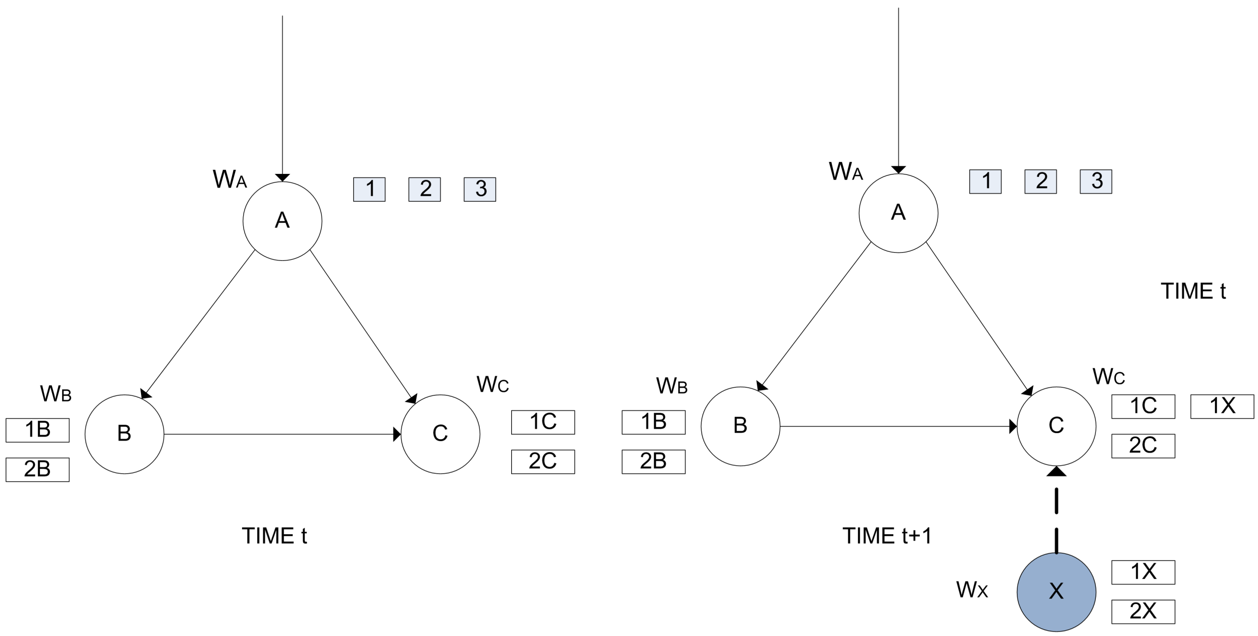

Fig. 2. Example of RLNC used to detect a new node (Node X) that joins the network and becomes a neighbour of Node C. The coloured squares are the coding vectors received till the time of observation at a node. These coding vectors spanned a particular subspace that has special properties from which it is possible to infer some characteristics of the network.

of ad hoc networks and uses DYMO as an efficient and up to date ad hoc routing protocol. In particular, the concept is deploying RLNC at the bottom of DYMO. Figure 3 shows the place of Network Coding operations in the stack. RLNC is placed between Network and MAC layers in order to make available the information on subspaces spanned by coding vectors at the Network layer to make DYMO protocol more energy efficient. DYMO as a reactive protocol does not need big routing tables and has a low delay for finding a route to destination. Nevertheless DYMO enabled node clear benefits if an up-to-date complete list of neighbours is available, since this will improve its control operations, such as the forwarding of RREQ, replying via RREPs and even flooding RERR to neighbours to correcting and updating routing tables. The passive information sent by RLNC can be extremely useful for DYMO to perform these operations and to increase DYMO's performance and energy efficiency. Neighbour discovery via RLNC is done locally by each node without the creation of any extra control packets; this approach indirectly decreases the traffic and interferences between packets. On the other hand, DYMO can also provide RLNC several paths between all pair nodes relevant for the execution of network coding operations.

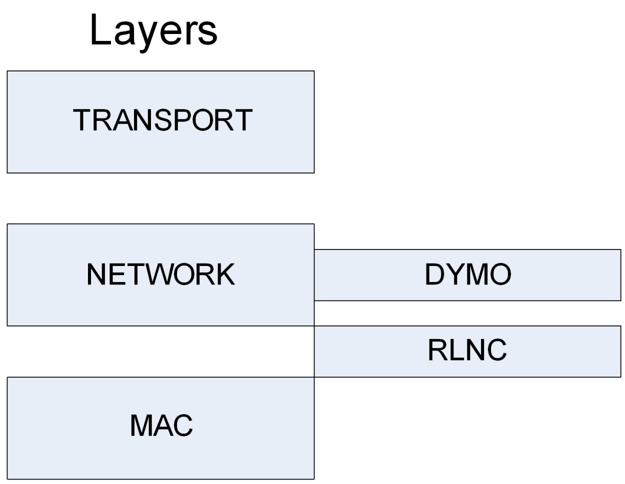

Fig. 3. Protocol stack on a RLNC/DYMO enabled node. In particular, RLNC is placed at the bottom of DYMO to provide it the (passively collected) neighbours list.

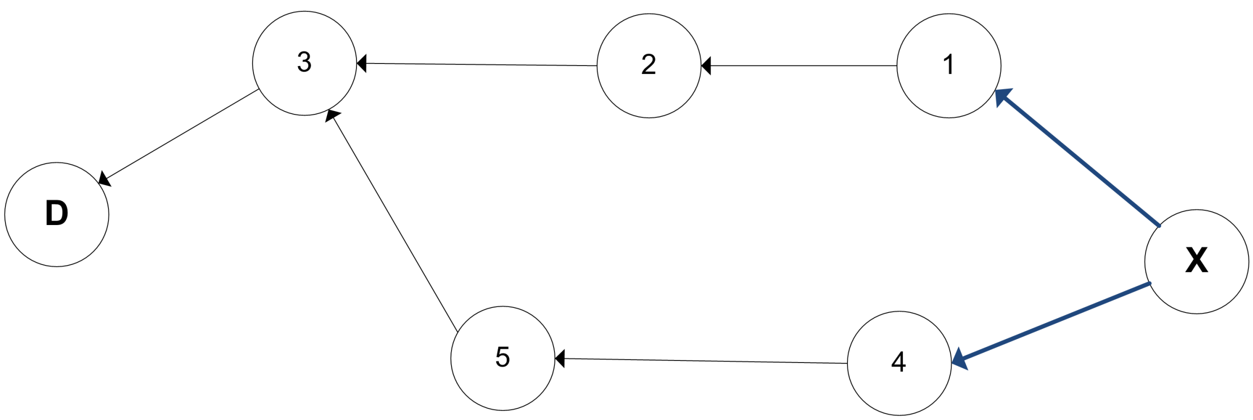

Fig. 4. Representation of a scenario in which a new Node X joins the network by connecting and communicating to Node 1 and Node 4.

IV. Analysis

Figure 4 depicts an example to analytically evaluate the energy gain due to the deployment of Network Coding for neighbouring discovery. A new Node X joins the network by starting the communication with Node 1 and Node 4. The aim is to send information to a destination node called Node D. In a classical scenario in which Routing is only used in the transmissions, all the nodes 2, 3, 4, 5 have to send a control packet to inform the next hop of the presence of a new neighbour (before starting the transmission of data). By using random linear network coded information packets the transmission of the control packets among the nodes is avoided and translated into the process of the coding vectors and the subspaces they

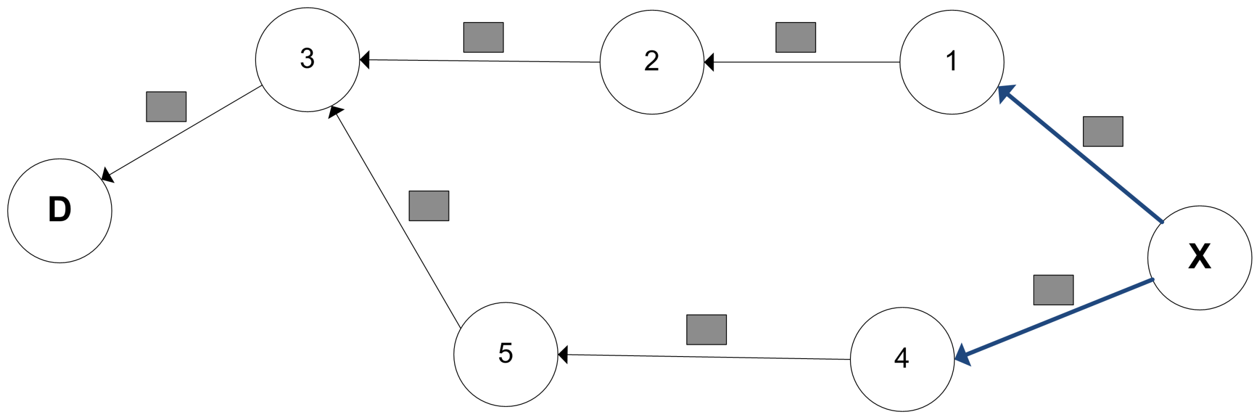

Fig. 5. Transmission of random linear network coded data packets (grey) sent among the nodes that once processed can provide the information on the new neighbour. The only control packets sent are the ones sent by Node X to get connected to Node 1 and 4.

span. In particular, the information on the subspaces can provide the knowledge that Node X joined the network and the relations among the subspaces can show that Node X is neighbour of Node 1 and Node 4 to the remaining Nodes 2, 3, 5. A mathematical analysis of the energy gain due to RLNC based on the previous example follows. Let $f(x) = c$ (measured in Joule/bit) be a constant cost function that defines how much energy is needed to transmit each bit. Let n be the number of bits of a data packet and $k < n$ the size of a control packet.

- Routing: $\Delta E_R = 7kc + 7nc = 7c(k+n)$ Joule/bit
- RLNC: $\Delta E_{RLNC} = 2kc + 7nc = c(2k+7n)$ Joule/bit

Then, the Relative Average Energy Reduction per bit (RAER) becomes

$$RAER[\%] = 1 - \frac{c(2k+7n)}{7c(k+n)} \cdot 100 = 1 - \frac{2k+7n}{7k+7n} \cdot 100 \tag{1}$$

By considering data packets of length $n = 100$ and control packets of length $k = 40$ the RAER becomes

$$RAER[\%] = 1 - \frac{80+700}{280+700} \cdot 100 = 20\% \tag{2}$$

Finally, Figure 6 shows the variation of RAER according to the size of control packets sent.

V. Conclusion

In this paper we have discussed a way to improve routing in MANETs by deploying RLNC to passively discover neighbouring nodes. The proposed approach uses the variation of the characteristics of the subspaces spanned by coding vectors, appended to the encoded information packets, to efficiently detect neighbours without applying expensive control signalling at the routing level. This condition improves

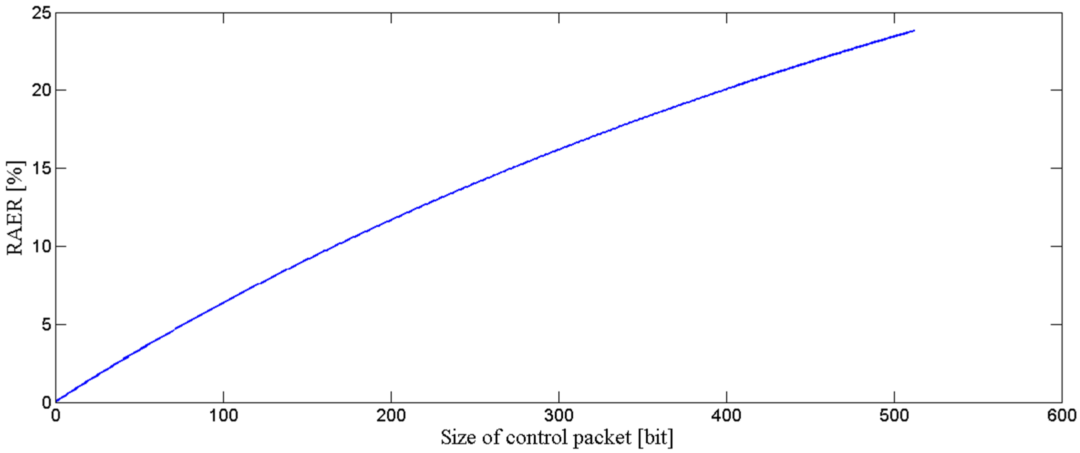

Fig. 6. Representation of RAER depending on the size of control packets involved.

DYMO operations making it to perform faster and also to achieve higher energy efficiency. On the other hand DYMO also provides RLNC several paths between all pair nodes, essential for a better execution of network coding operations. Finally, an analytical evaluation of the energy reduction has been presented.

This paper represents a proof-of-concept, validated by our preliminary results. The authors aim to further research this concept by developing supplementary research work on the following topics:

- how DYMO/AODVv2 and network coding interact and exchange information;
- to efficiently append RLNC (i.e. indications of the generation and coding vectors) to the standard packet of DYMO;
- an updated procedure to process the information about the subspaces and to disseminate this information among the nodes.

REFERENCES

[1] R. Ahlswede, N. Cai, S.-Y. R. Li, and R. Yeung, "Network information flow," *IEEE Information Theory*, vol. 46, no. 4, pp. 1204–1216, 2000.

[2] M. Jafarisiavoshani, C. Fragouli, and S. N. Diggavi, "Subspace properties of randomized network coding," in *IEEE Information Theory Workshop on Information Theory for Wireless Networks, 2007*, Jul. 2007, pp. 1–5.

[3] M. Jafarisiavoshani, C. Fragouli, S. N. Diggavi, and C. Gkantsidis, "Bottleneck discovery and overlay management in network coded peer-to-peer systems," in *Proceedings of the ACM workshop on Internet network management (IMN)*, 2007, pp. 293–298.

[4] G. Sharma, S. Jaggi, and B. K. Dey, "Network tomography via network coding," in *IEEE Information Theory and Application Workshop*, 2008, pp. 151–157.

[5] H. Yao, S. Jaggi, and M. Chen, "Network coding tomography for network failures," in *Proceedings of the IEEE International Conference on Computer Communications (INFOCOM)*, 2010, pp. 1–5.

[6] Y. Vardi, "Network tomography: Estimating source-destination traffic intensities from link data," *Journal of the American Statistical Association*, vol. 91, no. 433, pp. 365–377, Mar. 1996. [Online]. Available: http://dx.doi.org/10.2307/2291416

[7] T. Ho, M. Médard, R. Koetter, D. R. Karger, J. S. M. Effros, and B. Leong, "A random linear Network Coding approach to multicast," *IEEE Transactions on Information Theory*, vol. 52, no. 10, pp. 4413–4430, 2006.

[8] S. K. Bisoyi, S. Sahu, and C. V. Raman, "Performance analysis of Dynamic MANET On-demand (DYMO) routing protocol," in *International Conference (ACCTA-2010)*, vol. 1, no. 2-3-4, 2010.

[9] M. Illyas, Ed., *The handbook of ad hoc wireless networks*. CRC press Boca Raton, 2003.

[10] "Dynamic MANET On-demand (DYMO), routing draft-ietf-manet-dymo-21." [Online]. Available: http://tools.ietf.org/html/draft-ietf-manet-dymo-22

[11] "Dynamic MANET On-demand (AODVv2) routing draft-ietf-manet-dymo-22." [Online]. Available: http://tools.ietf.org/html/draft-ietf-manet-dymo-21

[12] "Ad hoc On-Demand Distance Vector (AODV), routing ietf draft." [Online]. Available: http://www.ietf.org/rfc/rfc3561.txt

[13] "Dynamic Source Routing protocol (DSR), ietf draft." [Online]. Available: http://www.ietf.org/rfc/rfc4728.txt

[14] M. Jafarisiavoshani, C. Fragouli, and S. N. Diggavi, "Subspace properties of network coding and their applications," *IEEE Transactions on Information Theory*, vol. 58, no. 5, pp. 2599–2619, May 2012.