

Routing and Network Coding over a Cyclic Network for Online Video Gaming

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Abstract—Online video games are getting more popular, attracting a continuously growing number of players. The main performance metrics of this application on the network level are packet ordering, communication throughput and transmission latency. Nowadays there is an interest in cyclic logical network topologies for online gaming, due to the easiness to preserve the packet order over cycles. Unfortunately, this approach increases the end-to-end transmission delays. In our paper, two main contributions are therefore presented. Firstly, it is shown that one can improve the latency of a gaming protocol over a single-cycle topology by the network coding (NC) approach. The corresponding NC-based routing protocol has been designed and analysed; it outperforms the best routing protocol without NC. Secondly, from the NC viewpoint, the example of online gaming is not a trivial one, given that the corresponding communication protocol is not multicast. Therefore, it is shown that there exists a NC gain (namely, up to 14% in transmission latency) even in case of a mixed communication protocol with broadcast and unicast transmission flows.

Index Terms—Online video gaming, routing protocol, latency, cyclic topology, network coding.

I. INTRODUCTION

TO improve the performance of emerging real-time group-based multiuser applications, e.g., multiplayer online games, Internet-of-Things or mobile group services, a distributed 2-tier architecture has been largely proposed [1]–[3]. In such an architecture, user instances are distributed among multiple servers in order to meet the delay constraint imposed by the real-time service requirement. Thus one server handles one communication group, usually by organizing a multicast transmission among the nodes. Basically, there are two topologies to communicate within a communication group: trees and cycles. A cycle-based network is well suited for applications that require ordering, low-overhead control protocol and inherent failure tolerance as illustrated in [4]–[6]. Compared to trees, the cycle topologies improve throughput and reliability, but cause an additional latency.

The focus of our paper is online video gaming – a user application of increasing popularity (e.g., the number of active players in *League of Legends* raised from 11.5 billions/month in 2011 to more than 100 billions/month in 2016). It belongs to the class of real-time multiuser applications, and it is evaluated over such performance metrics as *throughput*, *transmission latency* and *packet ordering*, the latter ensuring consistency within the game [7]. Given the order-preserving

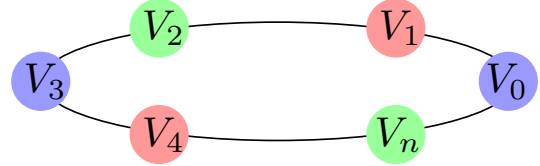


Fig. 1: Single-cycle topology for online gaming with $n = 5$. Also, $V_0 = S$. Node subsets \mathcal{V}_1 , \mathcal{V}_2 and \mathcal{V}_3 are given by blue, red and green.

setup of online gaming, it is therefore relevant to perform the routing over a cyclic logical network as it has been already proposed in [8]¹. However, the issue of transmission latency should be properly addressed.

Our proposition is to improve the latency over cyclic topologies by using Network Coding (NC) based protocols [9]. It is known that NC improves the transmission delay in multicast [11] and some unicast [10] scenarios, and also for several interesting cases over cyclic networks [11]–[14]. However, the specificity of online gaming traffic is to be taken into account – the communication between a game server and player nodes is not based on multicast but is a mixture of one broadcast and multiple unicasts which differs from the state-of-the-art of NC protocols. We consider this particular communication scheduling and proceed as follows. First, an efficient routing protocol (without NC) with small communication latency is built as a reference. Then, a NC scheme for online gaming communication protocols over cyclic networks is proposed, and its gain in terms of latency is estimated. For the seek of simplicity, the network with a single cycle is considered, this corresponds to one single proximity-defined logical subnetwork within a game.

II. SYSTEM MODEL AND NOTATION

Let the logical network of an online game contain a single cycle, connecting the game server S and n game players. It is represented by a cycle $G = (V, E)$ (see Fig.1) with the set of nodes $\mathcal{V} = \{V_0 = S, V_1, \dots, V_n\}$, and the set of links E . For simplicity, let the network be homogenous so that each link $e \in E$ may transmit one packet per time unit (t.u.). Online

¹There, logical cycles are organised to gather players using some proximity criteria, e.g., their geographical closeness on the game map [8].

game traffic is periodic with a *communication period* T [t.u.] and contains $n + 1$ flows as follows:

- a broadcast flow from V_0 to all $V_i \in V \setminus V_0$ to communicate the current game instance;
- n unicast flows from any $V_i \in V \setminus V_0$ to V_0 carrying players' actions.

Also, let us denote by L the total number of packets transmitted through the network during one *communication period* T .

The directions of $n + 1$ flows described above imply two source-destination sets:

- $\mathcal{S}_1 = \{V_0\}$ and $\mathcal{D}_1 = \{V_1, \dots, V_n\}$: the node V_0 broadcasts a common message M_0 to the set \mathcal{D}_1 ;
- $\mathcal{S}_2 = \{V_1, \dots, V_n\}$ and $\mathcal{D}_2 = \{V_0\}$: each node V_i in \mathcal{S}_2 has a private message M_i to send to V_0 .

Given n , \mathcal{S}_1 , \mathcal{D}_1 , \mathcal{S}_2 and \mathcal{D}_2 defined above, we distinguish the *routing problem* which aims to find a routing \mathcal{R} minimizing the couple (T, L) , and the *network coding (NC) problem* which consists to find a network code \mathcal{C} and a routing protocol \mathcal{R}_C minimizing (T, L) .

For later use, let $D \triangleq \lceil n/2 \rceil$ and $d \triangleq \lfloor D/2 \rfloor = \lfloor \frac{n+1}{4} \rfloor$.

A. Transmission Rules and Related Transmission Scheduling

In order to solve the routing and NC problems, transmission rules within G are to be fixed. Let assume them as following:

- 1) A node V_i , when sending a message M , broadcasts it to its closest neighbours V_{i-1} and V_{i+1} , where the index addition/subtraction is performed modulo $n + 1$ (*possibility to broadcast*);
- 2) During one time unit, each node is either in the receiving or in the sending mode (*half-duplex regime*);
- 3) A node cannot receive two simultaneous messages from its neighbours (*collision*).

For the rules above, it can be shown that the best transmission schedule, giving the smallest T with the best collision avoidance, is determined as follows [14]. If $n + 1$ is divisible by 3, i.e. $(n + 1)|3$, then the set of nodes V is divided into 3 disjoint subsets \mathcal{V}_1 , \mathcal{V}_2 and \mathcal{V}_3 so that a node from a subset \mathcal{V}_i is at least at distance 3 from another node from the same subset² (refer to Fig 1 for illustration). Further, the *3-phase transmission schedule* is adopted: the data transmission is organised in *rounds*, each lasting 3 t.u.; a subset \mathcal{V}_i is allowed to broadcast during one time unit slot, while other subsets will be only listening, thus avoiding collisions. W.l.o.g., we assume that the subset \mathcal{V}_i broadcasts during the time unit slot i , $i = 1, 2, 3$. When $(n + 1) \nmid 3$, 4 disjoint groups $\mathcal{V}_1, \dots, \mathcal{V}_4$ are formed under the same distance constraint, and a *4-phase transmission schedule* is put on place.

III. A MOTIVATING MULTICAST EXAMPLE

The state-of-the-art of network-coded communication protocols over cyclic topologies is mostly based on the multicast scenario, where each node V_i has a message M_i to send to all other nodes in the network, for all possible values of i .

In this case the use of NC is beneficial. Let us illustrate it on the following example by comparing two communication protocols, with and without NC.

Example 1: Consider the *circular routing* for multicast over a single-cycle network with $n + 1$ nodes V_0, \dots, V_n . Here the messages are forwarded over the cycle in one direction (clockwise or counterwise), following the 3-phase or 4-phase transmission schedule described above. The transmission continues until any message M_i reaches all the nodes in $V \setminus V_i$.

Lemma 1: The minimum communication period T for Example 1 is bounded as $3n \leq T \leq 4n$, while the total number L of messages to transmit over the network is $L \leq \lfloor (n+1)/3 \rfloor T$.

Proof. The proof is straightforward. If $(n+1)|3$, then exactly n rounds of the 3-phase transmission are needed so that M_i reaches all its destinations. Otherwise, n rounds of the 4-phase transmission will be used. As for the result on L , note that at most $\lfloor (n+1)/3 \rfloor$ messages are sent at each t.u. \square

Example 2: Consider the multicast problem over the single-cycle network, where the nodes are allowed to perform NC operations. Then, Algorithm 1 below can be adopted. Note that the algorithm was first described in [14] and here we give it when $(n + 1)|3$ only, for the seek of simplicity.

Algorithm 1 Multicast with NC [14] when $(n + 1)|3$

Initialisation: V_i is allocated to the subset \mathcal{V}_j , $j = (i \bmod 3) + 1$, $0 \leq i \leq n$. Each V_i has a message M_i to multicast.

For $0 \leq t \leq \lceil n/2 \rceil$, **perform the 3-phase transmission:**

During 3 t.u., a node V_i ($0 \leq i \leq n$) does the following (the order of operations depends on its subset index j):

- 1) Reception of a message from the right $M_{i+1}^{\rightarrow}(t)$;
- 2) Reception of a message from the left $M_{i-1}^{\leftarrow}(t)$;
- 3) Broadcast of the current message $M_i(t)$, where

$$M_i(t) = \begin{cases} M_i, & t = 0; \\ M_{i-1}^{\leftarrow}(t-1) \oplus M_{i+1}^{\rightarrow}(t-1), & t > 0. \end{cases}$$

Lemma 2: Given the NC-based multicast protocol from Example 2, the minimum communication period T_{NC} is bounded as $3\lceil \frac{n}{2} \rceil \leq T_{NC} \leq 4\lceil \frac{n}{2} \rceil$, and the number of messages $L_{NC} \leq \lfloor (n+1)/3 \rfloor T_{NC}$.

Proof. At round $t = 0$, V_i receives M_{i-1} from the left and M_{i+1} from the right³. At round $t > 0$, V_i possesses already the messages M_{i-t} and M_{i+t} . Moreover it receives $M_{i-1}(t) = M_{i-t-1} \oplus M_{i-t+1}$ and $M_{i+1}(t) = M_{i+t-1} \oplus M_{i+t+1}$. So it decodes M_{i-t-1} and M_{i+t+1} by XOR-ing: $M_{i\pm t\pm 1} = M_{i\pm 1}(t) \oplus M_{i\pm t}$. At round $t = \lceil n/2 \rceil$, V_i receives the last missing message from its farthest node(s). As the duration of the round might be 3 or 4 t.u. (depending on n), one gets lower and upper bounds on T_{NC} . The calculation of L_{NC} is straightforward. \square

Note that, in the half-duplex multicast example, NC improves T by $1/2$ [14].

IV. PROTOCOLS FOR ONLINE GAMING

The system model for online gaming application is given in Section II. The sets \mathcal{S}_1 , \mathcal{D}_1 , \mathcal{S}_2 and \mathcal{D}_2 are specific to online

²By distance one understands the number of hops between the two nodes.

³here and below the index addition/subtraction is performed modulo $(n+1)$

Algorithm 2 Routing protocol when $(n+1)|3$

Initialisation: V_i is allocated to the subset \mathcal{V}_j , $j = i \bmod 3$, $0 \leq i \leq n$. Each V_i has a message M_i to transmit.

3-phase round for $t = 0$: A node V_i ($0 \leq i \leq n$) performs the operations as in Algorithm 1 for $t = 0$.

4-phase round for $1 \leq t \leq d$:

During first 3 t.u., at each time unit ℓ ($\ell = 1, 2, 3$) the set \mathcal{V}_i broadcasts while the other sets are silent. Moreover,

- if $V_i \in S_{\rightarrow} = \{V_0, \dots, V_{D-t}\} \setminus V_0$, it broadcasts $M_i(t) = M_{i+1}^{\rightarrow}(t-1)$;
- if $V_i \in S_{\leftarrow} = \{V_{n-D+t+1}, \dots, V_{n+1} = V_0\} \setminus V_0$, it broadcasts $M_i(t) = M_{i-1}^{\leftarrow}(t-1)$.

During the last t.u., nodes V_t and V_{n+1-t} broadcast M_0 .

3-phase round for $d+1 \leq t < D$:

During first 3 t.u., at each time unit ℓ ($\ell = 1, 2, 3$) the set \mathcal{V}_i broadcasts while the other sets are silent. Moreover,

- if $V_i \in S_{\rightarrow} = \{V_0, \dots, V_{D-t}\} \setminus V_0$, it broadcasts $M_i(t) = M_{i+1}^{\rightarrow}(t-1)$;
 - if $V_i \in S_{\leftarrow} = \{V_{n-D+t+1}, \dots, V_{n+1} = V_0\} \setminus V_0$, it broadcasts $M_i(t) = M_{i-1}^{\leftarrow}(t-1)$;
 - V_t and V_{n+1-t} broadcast M_0 .
-

game protocols and give rise to a non-multicast scenario. Therefore, even if Algorithm 1 could a priori be used for online gaming applications, it does not guarantee minimum values for T and L . Moreover, the amount of calculations to perform would be quite high, which is an issue for a real-time, bandwidth-consuming application such as online gaming.

Let us design appropriate routing and NC-based protocols for the setup in Section II.

A. Optimized Routing

We propose Algorithm 2 as a routing protocol without NC for online gaming. It is in fact an optimised version of the *shortest-path routing* algorithm. For simplicity, the algorithm is described when $(n+1)|3$. To illustrate Algorithm 2, Fig.2 presents a time diagram for $n = 5$ ($D = 3$ and $d = 1$). At round 0, the nodes send their own messages in 3 t.u. At round 1, V_0 and V_3 remain silent, thus V_1 and V_5 send two messages each, and V_2 and V_4 send messages of their neighbours. During round 2, the nodes V_2, \dots, V_5 should remain silent except V_4 which communicates M_0 to V_3 . V_1 forwards M_3 to V_0 .

Remark 1: If $(n+1) \nmid 3$, then 4 disjoint groups $\mathcal{V}_1, \dots, \mathcal{V}_4$ are formed following the rules. Let $r = (n+1) \bmod 3$ and let $\mathcal{V}_4 = \emptyset$ if $r = 0$, $\mathcal{V}_4 = \{V_{\lceil n/2 \rceil}\}$ if $r = 1$ and $\mathcal{V}_4 = \{V_{\lfloor n/2 \rfloor}, V_{\lceil n/2 \rceil}\}$ if $r = 2$. Then

$$\begin{aligned} \mathcal{V}_1 &= (\{V_i : i \bmod 3 = 0, i \leq \lfloor n/2 \rfloor\} \cup \\ &\quad \{V_i : i \bmod 3 = r, i > \lfloor n/2 \rfloor\}) \setminus \mathcal{V}_4 \\ \mathcal{V}_2 &= (\{V_i : i \bmod 3 = 1, i \leq \lfloor n/2 \rfloor\} \cup \\ &\quad \{V_i : i \bmod 3 = (r+1) \bmod 3, i > \lfloor n/2 \rfloor\}) \setminus \mathcal{V}_4 \\ \mathcal{V}_3 &= (\{V_i : i \bmod 3 = 2, i \leq \lfloor n/2 \rfloor\} \cup \\ &\quad \{V_i : i \bmod 3 = (r+2) \bmod 3, i > \lfloor n/2 \rfloor\}) \setminus \mathcal{V}_4 \end{aligned}$$

Also, Algorithm 2 is modified accordingly: the round $t = 0$ lasts 4 t.u. (each node subset broadcasts during 1 t.u. and stays

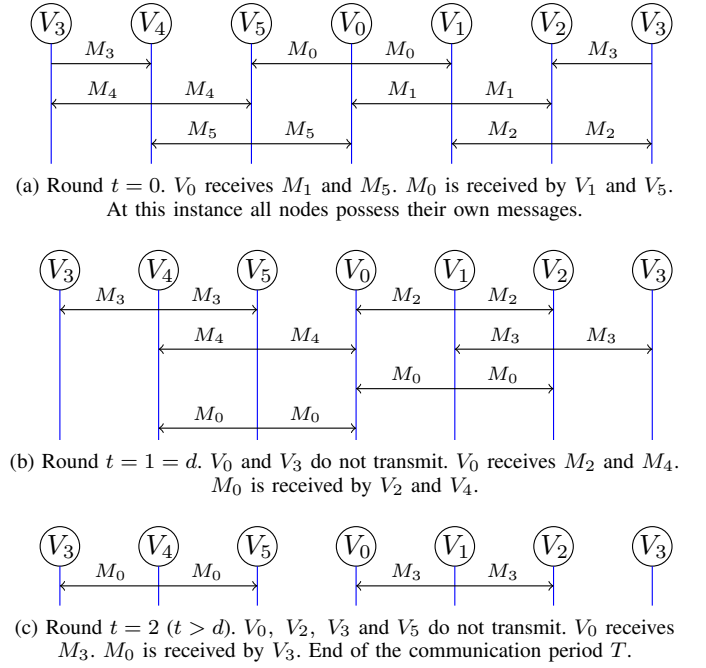


Fig. 2: Example for $n = 5$. Similar to Fig.1, $\mathcal{V}_1 = \{V_0, V_3\}$, $\mathcal{V}_2 = \{V_1, V_4\}$, $\mathcal{V}_3 = \{V_2, V_5\}$.

silent during 3 t.u.). Thanks to the careful choice of \mathcal{V}_4 , the rounds for $t > 0$ stay unchanged⁴.

Theorem 1: The period T of Algorithm 2 is bounded as

$$3\lceil n/2 \rceil + \lfloor \frac{n+1}{4} \rfloor - 2 \leq T \leq 3\lceil n/2 \rceil + \lfloor \frac{n+1}{4} \rfloor + 1,$$

and $L = \lceil n/2 \rceil (\lceil n/2 \rceil + 3) - 1$.

Proof. The proof is by counting. Let $(n+1)|3$. By shortest-path routing over the cycle with $n+1$ nodes, a message M_i will be received by a destination in at most D hops. The hops make part of the rounds of Algorithm 2, thus, for the round $t = 0$, 3 t.u. will be used for one hop. The total number of messages sent at $t = 0$ is $n+1$. Moreover, for $1 \leq t \leq d$, we have the following. The nodes V_i with $1 \leq i \leq j$ and with $n+1-d \leq i \leq n$ have two messages to forward: a message M_j , $j \in \{i+1, \dots, i+d\} \cap \{j-d, \dots, j-1\}$, and M_0 . These nodes will use one additional t.u. so all of them will last 4 t.u. Note that the rest of nodes will be silent as they have no new messages to send. As for the rounds with $d+1 \leq t < D$, M_0 is now to be transmitted by nodes with indices in $\{d+1, \dots, \lfloor n/2 \rfloor - 1\} \cap \{\lfloor n/2 \rfloor + 2, \dots, n-d\}$. These nodes have no other messages to forward thus they send M_0 within 3 t.u. during which the nodes V_i with $1 \leq i \leq j$ and with $n+1-d \leq i \leq n$ forward messages to V_0 . Also, it can be shown that at any round $1 \leq t < D$, $n+2-2t$ messages will be sent in total. Finally, if $(n+1) \nmid 3$, one more t.u. will be used at $t = 0$, and the rest of protocol will be unchanged. This give us the upper bound on T , $T \leq 4d+3(D-d-1)+4$, as well as $L = n+1 + \sum_{t=1}^{D-1} (n+2-2t)$.

Also, by better transmission organisation, it is possible to save some t.u. for $t = D-2$ and $t = D-1$, as there are many

⁴ Note that, if $|\mathcal{V}_4| = 2$, it seems to be a collision in transmitting $M_{\lfloor n/2 \rfloor}$ and $M_{\lceil n/2 \rceil}$ at $t = 0$. However there is no loss for $M_{\lfloor n/2 \rfloor}$ and $M_{\lceil n/2 \rceil}$, as they are successfully received by $V_{\lfloor n/2 \rfloor - 1}$ and $V_{\lceil n/2 \rceil + 1}$ respectively.

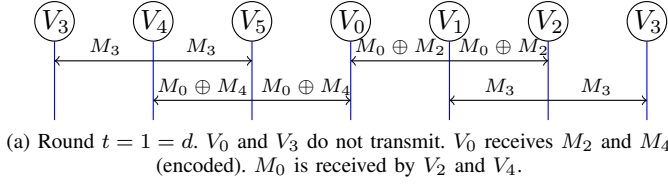


Fig. 3: Round $t = 1$ of the NC protocol for $n = 5$.

silent nodes in the network, and the simultaneous transmission by nodes from different subsets does not create collisions. It can be shown that this gain is at most 3 t.u. \square

B. NC-Based Protocol

Let the nodes perform NC operations. Then the routing protocol above can be modified as follows.

Algorithm 3 NC-based protocol when $(n+1)|3$

Initialisation and round $t = 0$: As in Algorithm 2.

3-phase round for $1 \leq t \leq d$: At each time unit ℓ ($\ell = 1, 2, 3$) the set \mathcal{V}_i broadcasts while the other sets are silent.

- if $V_i \in S_{\oplus} = \{V_t, V_{n+1-t}\}$, it broadcasts $M_i(t) = M_{i-1}^{\leftarrow}(t-1) \oplus M_{i+1}^{\rightarrow}(t-1)$;
- if $V_i \in S_{\rightarrow} = \{V_0, \dots, V_{D-t}\} \setminus V_0$, it broadcasts $M_i(t) = M_{i+1}^{\rightarrow}(t-1)$;
- if $V_i \in S_{\leftarrow} = \{V_{n-D+t+1}, \dots, V_{n+1} = V_0\} \setminus V_0$, it broadcasts $M_i(t) = M_{i-1}^{\leftarrow}(t-1)$.

3-phase round for $d+1 \leq t < D$: As in Algorithm 2.

One can see that the transmissions at rounds $1 \leq t \leq d$ have been modified. To illustrate the proposed modification, let us take the example on Fig. 2. The new protocol would modify the transmission at $t = 1$, it becomes as it is shown in Fig.3. Note that 2 t.u. are saved thanks to NC operations. More generally, the following is stated:

Theorem 2: For Algorithm 3, one has $3\lceil n/2 \rceil - 2 \leq T_{NC} \leq 3\lceil n/2 \rceil + 1$, and $L_{NC} = \lceil n/2 \rceil (\lceil n/2 \rceil + 3) - 2\lfloor \frac{n+1}{4} \rfloor - 1$.

Proof. Owing to NC operations, the nodes, having two messages to forward, send their XORs. Note that the nodes receiving XORs are always able to decode new messages. Thus the rounds with $1 \leq t \leq d$ last 3 t.u. instead of 4, and the number of transmitted messages is decreased by 2 in each round. By counting the number of messages as transmissions similar as for Theorem 1, one obtains that $3D/2 - 3 \leq T \leq 4\lfloor D/2 \rfloor + 3\lceil D/2 \rceil$ and $L_{NC} = D(n+3-D) - 1 - 2d$. \square

V. DISCUSSION

Table I gives the values of T and L for four protocols, described in the paper (multicast circular routing, NC-based multicast from Algorithm 1, optimised protocols without and with NC from Algorithms 2 and 3). One can see that the optimised routing protocol (Algorithm 2) has better performance in terms of T and L , compared to multicast protocols. Moreover, Algorithm 3 allows to obtain even larger gains, in particular around 14% compared to Algorithm 2 in terms of T , when n is sufficiently large.

n	T (LB/UB), L			
	Circular routing	Algorithm 1	Algorithm 2	Algorithm 3
7	21/28, 42	12/16, 24	12/15, 23	10/13, 19
8	24/32, 72	12/16, 36	12/15, 27	10/13, 23
9	27/36, 81	15/20, 60	15/18, 34	13/16, 30

TABLE I: Comparison of T (lower bound and upper bound) and L for protocols from Sections III-IV.

Algorithm 3 is consistent from the game point of view as the arrival order of packets at V_0 is predetermined by the placement of nodes within the cycle: at each round t , V_0 receives messages M_{t+1} and M_{n-t} . This fact can be taken into account during the choice of nodes V_1, \dots, V_{n-1} , in order to design a desired order of message arrivals at V_0 .

The NC gain of Algorithm 3 is due to the possibility to broadcast messages to close neighbours (transmission rule 1). This condition is easy to satisfy in some kind of networks, i.e., in wireless mesh networks [14]. In wireline networks, broadcast may be implemented by means of the IP-multicast [15]. Note that, if broadcast is not an option and one has to send messages to the neighbours sequentially (i.e., classical routing in wireline networks), the gain is lost and Algorithm 3 behaves as Algorithm 2. Note that, in contrast to the broadcast constraint, the half-duplex constraint (transmission rule 2) does not limit the usefulness of NC. For full-duplex transmissions, Algorithms 2 and 3 can be modified accordingly.

Our future work will extend our simple system model to incorporate some properties of gaming protocols, in the order of relevance: a) heterogenous transmission delays between the neighbours in the cycle network; b) difference in the size between the message M_0 and other nodes messages and c) packet losses. The cyclic topology is also going to be compared with a tree-like topology by simulations in NS-3.

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