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Resource Tuned Optimal Random Network Coding for Single Hop Multicast future 5G Networks

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***Abstract*—Optimal random network coding is reduced complexity in computation of coding coefficients, computation of encoded packets and coefficients are such that minimal transmission bandwidth is enough to transmit coding coefficient to the destinations and decoding process can be carried out as soon as encoded packets are started being received at the destination and decoding process has lower computational complexity. But in traditional random network coding, decoding process is possible only after receiving all encoded packets at receiving nodes. Optimal random network coding also reduces the cost of computation. In this research work, coding coefficient matrix size is determined by the size of layers which defines the number of symbols or packets being involved in coding process. Coding coefficient matrix elements are defined such that it has minimal operations of addition and multiplication during coding and decoding process reducing computational complexity by introducing sparseness in coding coefficients and partial decoding is also possible with the given coding coefficient matrix with systematic sparseness in coding coefficients resulting lower triangular coding coefficients matrix. For the optimal utility of computational resources, depending upon the computational resources unoccupied such as memory available resources budget tuned windowing size is used to define the size of the coefficient matrix.**

***Keywords*—Coding coefficients; computational complexity; lower triangular matrix; random network coding; sparse coding coefficients**

I. INTRODUCTION

WITH the increase in the user's high data demand, the scientists and researchers around the globe are working together to achieve a higher data rate. The third generation 3GPP are planning to launch 5G standards until 2020. Various latest technologies are in progress such as the use of high-frequency mm-wave bands [1-4], Device to Device Communication (D2D) [5], cooperative and Heterogeneous Network (HetNet) [6, 7], Coordinated Multipoint (CoMP) [8], Internet of things (IoT) [9], Carrier Aggregation (CA) [10], Cognitive Radio (CR) [11], Passive Optical Network (PON) [12], Massive Multiple Input Multiple Output (MIMO) [13], Non-Orthogonal Multiple Access (NOMA) [14], Mobile Ad-hoc Network (MANET) [15], Vehicular ad-hoc networks (VANET) [16], Fog Computing [17]. 5G will be capable of incorporating existing technologies such as several advance power optimizations techniques [18, 19] and optimal scheduling algorithms [20].

With the introduction of network coding in information theory [21], intermediate network nodes between source and destination nodes are capable of combining incoming packets or symbols from a finite field to generate functions with some algebraic operations defined over the field and forwarding to next nodes towards destination nodes as defined in (1) below. The outgoing message symbols (x_e) from node (v) are transformed from the incoming message symbols(x_d) with transfer function ϕ_v deployed at intermediate node (v) within which, the algebraic operations are defined.

$$x_e = \phi_v(x_d) \tag{1}$$

So, the network coding is an algorithm to generate functions (x_e) of incoming symbols (x_d) to node (v) and forwarding to the next hop nodes through outgoing links as defined by the (1). Theoretically, it has been accepted that information flow rates given by max-flow min-cut can be achieved with network coding deployed to intermediate nodes [22]. The authors [23] discussed linear network coding as simplified to (2) from (1) is rate optimal within multicast networks. For the implementation, computation of coding coefficients is challenging task and randomness in the topologies adds more complexities in the computation. The coding process at sending node and decoding process at receiving nodes involve multiplications, additions and inversion of symbols defined over the finite field. If the coding coefficients $k_{d,e}$ in (2) are randomly chosen from the finite field and the combination of symbols or packets are linear then the coding scheme is random linear network coding. Random network coding discussed by [24] which had been accepted to be robust to packet delay and losses. In general, coding coefficients are carried by encoded packets to destination nodes adding redundancies to the information flows so the bandwidth consumption

$$x_e = \sum_{d\epsilon In(v)} k_{d,e}\, x_d \tag{2}$$

Though network coding is accepted to be the technique that enhances network throughputs, fading channel may cause reduction in network throughput in large scale because error in

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a single encoded packet cause error in all the encoded packets in the generation during decoding process. For the remedy, feedback system can be used for retransmission, but the feedback system may not be available in all system and even if available feedback network information causes overhead to the system. So reduced network information flows over the network enhances the performance of the network coding scheme. The authors in [25] discusses the practical coding-aware routing network coding COPE which incorporates opportunistic listening and learning of neighbor states and determines the coding opportunity.

II. CONTRIBUTION

Computations of coding coefficients in (2) and coding and decoding process involves number of multiplications and additions which define the computational complexity [26]. It can be observed from (2) the encoding involves N^2 multiplications and $(N-1)*N$ additions. Since reduced complexity in network approaches to distributed computation, random network coding technique provides very simple distributed network system. Another approach for highly dense network architecture is cooperative communication architecture and wireless network with high mobility. So, the random network coding technique is efficient one for such distributed network architecture, but it adds complexity and still overhead to the network which equivalently consumes high energy and demands high power computational device. Reduced computational complexity during the coding and decoding process enhances the efficiency of the network coding scheme. If there is random number of slices of streams participating in network coding which defines the coding coefficient matrix size, then this randomness is the number of packets involved in encoding process and the randomness adds the security level to some extents.

Therefore, in this research work, a scheme for computation of systematic sparse coding coefficient for random network coding is developed and studied the performance such that it reduces the coding and decoding computational complexity and still enhances the security level with reduced complexity. Further reduction of computational complexity was studied in this research work introducing sub-generation of a generation which comparatively reduces the coding density. This paper is structured as follows. Section III includes literature review related to optimizing coding and decoding process in random network coding. In section IV, optimal scheme is proposed to reduce computational complexity. Section V deals with performance evaluation of the scheme proposed. Section VI concludes the work in this research and section VII deals challenges of optimization of network coding schemes.

III. LITERATURE REVIEW

Several researches have been conducted on complexity minimization in the computation of network coding coefficients to improve network performance in terms of throughput, end to end to delay, channel capacity, and network resources utilization. Ahlswede *et al.* [27] first introduced the Network Coding in their seminal paper that initially target to achieve maximum throughput capacity in theoretical and practical perspective for multicast and multi unicast transmissions. The authors [28] introduced random network coding for routing based transmission. They also demonstrated robustness for distributed transmission within the network for available network capacity. Ho *et al.* [29] analyzed and demonstrated the achievability of max bounds given by max-flow min-cut theory using random linear network code for co-related sources multicast. Guo *et al.* [30] proposed an algorithm for construction of efficient random network coding coefficient. They used bit-map rather than transmitting packet ID and coding coefficients which was generated according to packet from other users if received. To generate coding coefficient at sending nodes and destination nodes, random coding coefficients were generated with hash functions in pseudo-random manner. Thus, their algorithm reduces the network coding information over the network and in case of error in packet received, credit-based updating algorithm was used instead of Gaussian Elimination Algorithm.

Li *et al.* [31] proposed an algorithm for network coding such that partial decoding could be possible with previously received encoded packets. For this, they used lower triangular coding coefficient matrix which can facilitate partial decoding provided packets received previously were error free. They introduced sliding window which slides forward depending upon packets received without error and error information in the transmission would be fed back to the transmitter. The scheme was adaptive sliding window random network coding and simulation showed that their scheme outperformed over traditional random network coding in terms of network throughput and feedback information overhead over the feedback system. Zhang *et al.* [32] used the adaptive random network coding and scheduling proposed in [31] and used space diversity in which any of users can act as relay depending upon channel conditions as feedback information. In the algorithm proposed, packets are prioritized firstly and highest priority packets were network encoded and transmitted in first time slot and accordingly to lesser priority packets in later time slots. Partial decoding at destination nodes were carried out as ARNC was used and so applicable to the video stream with scalable video coding where lower priority packets are acceptable to be lost after hard deadlines. Similar study was conducted by Tassi *et al.* in [33] where sparsity is introduced according to priority layers, higher the priority higher the sparsity and convex resource allocation framework to optimize the code sparsity so minimization of coding and decoding complexity.

Yunyi and Tuanfa in [34] studied the complexity increased and decoding success rate for different field size. Nonzero coding coefficient scheme for field size of 8 had best decoding success rate among different field size from 2 to 8. Addition of redundant rows in coding coefficient matrix was found to have higher decoding success rate but it needs higher bandwidth for coefficient matrix transmission to destination. In non-zero coding scheme process node combines all the information symbols without dropping any incoming links to the node. Noura, Martin and Agha [35] proposed a scheme to enhance the security measure of random linear network code with the use of updated dynamic keys to construct encoding coefficient matrix. To get higher security constraints authors modeled the transmission of coefficient matrices after encryption and reduction of computational complexity was obtained using coefficient matrix with elements from binary Galois Field with diagonal elements equal to one to make sure the matrix is invertible at receiving nodes. Simulation results showed satisfactory level of security and improved speed efficiency of lower computational complexity consuming lesser power of computation at nodes.

Heide *et al.* [36] introduced perpetual code as supplementary to random linear network coding and their experimental analysis showed improvement in tradeoff between computational complexity and code overhead over the network. The perpetual code introduces the sparsity and non-uniformity to the coding coefficients resulting fast encoding and decoding process and data protection respectively. The sparseness they introduced is equivalent to moving windows with small window size. For example, when they used tri-diagonal matrix is used, it is equivalent to use of window size three and moving by one step for next encoding process. Ho *et al.* [37] introduced universal network coding in the sense their scheme is independent of network parameters and robust scheme as its design is independent of network structure. Scheme can be implemented with only the topological information of the network. They summarized the implementation complexity in terms of polynomial of network parameters rather polynomial in log of field size in conventional network coding scheme. Feizi *et al.* [38] introduced sparse network coding coefficients to lower the coding complexity and the manipulations were brought to convert the encoding matrix to upper triangular matrix using packet coding density to make Gaussian elimination method of solving system of linear equations efficient. Since the decoding process has complexity of order $O(N^3)$, density of encoding packets should be controlled such that optimal decoding complexity was to be maintained depending upon the network resources available. Garrido *et al.* [39] introduced different approaches to control the density of encoding packets depending upon the feedback information from destination nodes at encoding nodes and they evaluated reduced complexity of 3.5 times without degradation of network performances. In [40], authors proposed a generation-based network coding (GNC) with an overhead-optimized decoder that combines precoding rate and random overlapping generations to obtain low decoding costs. The proposed code provides much sparser than the existing codes which having similar code overhead and network-induced overhead, while achieving low decoding cost for transmitting a moderate number of source packets.

Garrido *et al.* [41] proposed an absorbing Markov chain model to mimic the behavior of sparse network coding scheme which exploit an appropriate density function rather than decoder feedback to encoder and evaluate of density function. Latter Garrido *et al.* [42] further modified their tuned network coding scheme for higher accuracy for tuning. In that scheme, they proposed analytical model based on receiving linearly independent packets to determine the rank of decoder, the status of decoder, which reduces 70% of complexity with trade-off between computational complexity and network performance. For average decoding delay of the packets in sparse network coding, Zarei et al. [43] proposed absorbing Markov chain model to analyze partial decoding in sparse network coding that provides lower bound for decoding delay of a generation. It attained significant improvement in terms of average decoding delay per packet that is around 14% compared to random linear network coding (RLNC). Garrido *et al.* [44] studied the computational overhead of field size, packets in a generation and window size for sliding window scheme concluding reduction of window size to one-fourth of generation size to have insignificant effects on performance through low field size with large generation size has best performance.

IV. Proposed Coding Scheme

For simplicity, encoding matrix is of square matrix type and depending upon the number of packets or symbols to be encoded matrix size is defined. The encoding matrix is generated using some pseudorandom generator $\emptyset(N, K)$ where generator function uses the number of symbols (N) participating in network coding process and state of the generator (K) as seeds which are enough to generate the coefficient matrix $[\boldsymbol{\alpha}]$ both at transmitting nodes and receiving nodes. For the higher security measure, state (K) can also be synchronized random states.

For easy handling, first encoded packet could be encapsulated with number of packets participating in encoding process and state of the generator function for random state chosen as seed or different secured channel can be used to send the seed to generate random coefficient matrix at receiving nodes. As soon as the encoded packet is received at destination nodes, seed encapsulated can be used to generate decoding coefficients matrix which involves generation of coding matrix and then inversion of the matrix resulting decoding matrix $[\boldsymbol{\alpha}]$.

In the first network coding scheme proposed, systematic sparse is added to the encoding matrix resulting lower triangular matrix as shown in the matrix below, which reduces computational complexity in encoding from $O(N^2)$ to $O(N)$ and in decoding process from $O(N^3)$ to $O(N^2)$ with matrix inversion complexity reduction from $O(N^3)$ to $O(N)$ and the reduction in complexity is significant for larger value of N.

$$\begin{bmatrix} c_1 \\ c_2 \\ c_3 \\ \cdot \\ \cdot \\ c_N \end{bmatrix} = \begin{bmatrix} \alpha_{11} & 0 & 0 & 0 & \cdot\ \cdot & 0 \\ \alpha_{21} & \alpha_{22} & 0 & 0 & \cdot\ \cdot & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} & 0 & \cdot\ \cdot & 0 \\ \cdot & \cdot & \cdot & \cdot & \cdot\ \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot\ \cdot & \cdot \\ \alpha_{N1} & \alpha_{N2} & \alpha_{N3} & \cdot & \cdot\ \cdot & \alpha_{NN} \end{bmatrix} \begin{bmatrix} p_1 \\ p_2 \\ p_3 \\ \cdot \\ \cdot \\ p_N \end{bmatrix}$$

Elements of column vector **p** are native packets and are involved in encoding to generate encoded vector c and elements of matrix [α] are coding coefficients. Once the p_1 is extracted from the first encoded packet c_1, p_2 can be decoded immediately from encoded packet c_2 when it is received so the partial decoding is possible with this encoding coefficient matrix. Hence in this scheme, design of coding coefficients is such that, it has lower computational complexity both in coding coefficient generation and in encoding process. For the bandwidth efficiency, coding coefficients are generated both at sending nodes and receiving nodes by knowing size of coefficient matrix which is defined by the number of packets participating in the encoding process and state of the generator function as seed to the generator function. So, computational complexity can be expressed mathematically as:

$$C(N) = \beta_1 O(N) + \beta_2 O(N^2) + \beta_3 O(N)$$

From the equation (3) – β simply proportionality constant depends on computational resource above, it can be inferred that computational complexity is not linear function of order of packets involved in coding and information transmission. From the second term in the equation above, higher the order of packet involved in encoding-decoding, higher the complexity; so, complexity reduces with the lesser number of packets involved. But, much smaller number of packets involved in Network Coding reduces the benefits introduced by Network Coding scheme. Equation (3) above encourages the split of packet generation into optimally smaller sized sub-generation to reduce the computational complexity; however, there could exists range of sub-generation size for which split of packet generation size has not better performance. Size of sub-generation is function of resources – memory, computational speed – available in receiver side as the immediate decoding of the network coded packet is demanded to reduce the time wait to combine packets at receiver. Resource availability information is supposed to be transmitted to the sender via feedback systems.

The second network coding scheme proposed is resource tuned scheme where resource is computational capacity of encoder and decoder. In the scheme, number of packets in a generation was divided into sub-generation of equal number of packets in each sub-generation as possible such that number of computations is lower than that for single sub-generation of larger size. Though there could not be enough reduction in computational time for encoding because computational complexity in encoding is O(N), decoding process would have enough reduced computation time as the computational complexity in decoding is O(N^2). Following are the simple transformation of native packets to encoded child packets. Depending upon the resource available for computation at encoder and decoder, network coding process could have more transformation function execution as shown below.

$$\begin{bmatrix} c_1 \\ c_2 \\ c_3 \\ \cdot \\ \cdot \\ c_{\frac{N}{2}} \end{bmatrix} = \begin{bmatrix} \alpha_{1,1} & 0 & 0 & 0 & . & . & 0 \\ \alpha_{2,1} & \alpha_{2,2} & 0 & 0 & . & . & 0 \\ \alpha_{3,1} & \alpha_{3,2} & \alpha_{3,3} & 0 & . & . & 0 \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \alpha_{\frac{N}{2},1} & \alpha_{\frac{N}{2},2} & \alpha_{\frac{N}{2},3} & . & & . & \alpha_{\frac{N}{2},\frac{N}{2}} \end{bmatrix} \begin{bmatrix} p_1 \\ p_2 \\ p_3 \\ \cdot \\ \cdot \\ p_{\frac{N}{2}} \end{bmatrix}$$

$$\begin{bmatrix} c_{\left(\frac{N}{2}+1\right)} \\ c_{\left(\frac{N}{2}+2\right)} \\ c_{\left(\frac{N}{2}+3\right)} \\ \cdot \\ \cdot \\ c_N \end{bmatrix} = \begin{bmatrix} \alpha_{1,1} & 0 & 0 & 0 & . & . & 0 \\ \alpha_{2,1} & \alpha_{2,2} & 0 & 0 & . & . & 0 \\ \alpha_{3,1} & \alpha_{3,2} & \alpha_{3,3} & 0 & . & . & 0 \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \alpha_{\frac{N}{2},1} & \alpha_{\frac{N}{2},2} & \alpha_{\frac{N}{2},3} & . & & . & \alpha_{\frac{N}{2},\frac{N}{2}} \end{bmatrix} \begin{bmatrix} p_{\left(\frac{N}{2}+1\right)} \\ p_{\left(\frac{N}{2}+2\right)} \\ p_{\left(\frac{N}{2}+3\right)} \\ \cdot \\ \cdot \\ p_N \end{bmatrix}$$

Lower triangular matrix with all elements one for reduced decoding and coding complexity could be used but security issues will be gone up. If first encoded packet c_1 is tapped by the eavesdropper, information on the first packet can be decoded easily by the eavesdropper so the random network coding is not highly secure. So, the randomness in encoding coefficient matrix adds security to network flow and applicable to random network structures with varying number of intermediate nodes. As described in proposed network coding scheme above, the equation (3), further reduction of number or order of parent packets involved in Network Coding reduces the computational complexity. So, second network coding scheme further reduces the number of packets involved in network coding process reducing the second order of parent packets as in equation (3). However, for the secure of error free transmission of seed and other parameters to receiver is different study of channel coding other than network coding, network coding scheme has error correction capabilities.

V. PERFORMANCE EVALUATION

A. Computational Complexity and Energy

Reduced number of additions and multiplications reduce the coding complexity and time required to encode. The use of a smaller number of packets to generate encoded packet obviously reduces the number of computations during coding process. Since sparsity is added by introducing zeros above the diagonal, which is lower triangular coding coefficient matrix, encoding involves $(N^2+N)/2$ multiplications and $(N^2-N)/2$ additions whereas for the without sparse added, it involves N^2 multiplications and $(N^2+N)/2$ additions provided is the number of packets involved in network coding process. So, there is reduced number of operations during network coding process with sparsity. Introduction of sparseness to the coding coefficients has significant reductions in computational complexity during the decoding process as well. The increased the number of packets involved in encoding process increased the order of computation so higher computation time consumed and higher energy consumption. Complexity is reduced from O(N^2) to O(N) with sparse coding coefficients so the simulation validated smaller complexity compared to that of non-sparse coding coefficients case. It can also be simulated to observe the increased computation with the increase in size of symbols or encoding coefficients.

Similar reduction can be observed for complexity of decoding process when Gaussian Elimination is used to solve the equations at receiving nodes. Use of lower triangular matrix ease the decoding process and decoding can be done as soon as second encoded packet is received so the partial decoding. At receiving nodes, inversion of lower triangular matrix has only the computational complexity of O(N) whereas for the non-sparse coding coefficients involves that of O(N^3) complexity for the computation of inverse of coding coefficient matrix. But in Decoding process both the scheme involves computational complexity of O(N^2) and matrix inversion differentiate the complexity in total.

Simulation graph in fig. 1 and fig. 2 gives the number of floating-point operations for three different coding-decoding matrices namely; general coding matrix, lower triangular coding matrix and budget based lower triangular coding matrix with budget capable to compute sub-generation size of 10. Budget based scheme was found to be best in terms of floating-point operations in both coding and decoding process. Higher the number of floating-point operations higher number of computations which results higher the time consumption in coding and decoding process and higher the power consumptions. Higher number of computations requires higher number of memory space and so the cost of memory storages is also higher without sparseness in the coding coefficients. Thought graph in Figure 1 shows potential convergence for different generation sparsity proposition, study for higher generation size than 450 packets is not relevant because that is too larger size compared to practical scenario. This is because of the decoding resource capability of receiver; in general, smaller computational and time resources available at receiving side.

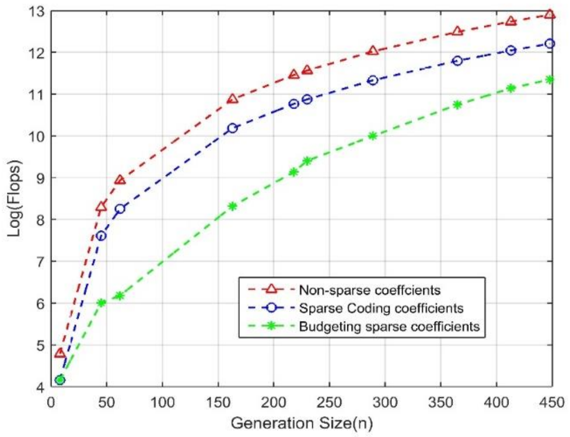

Fig. 1. Coding Complexity for different scheme

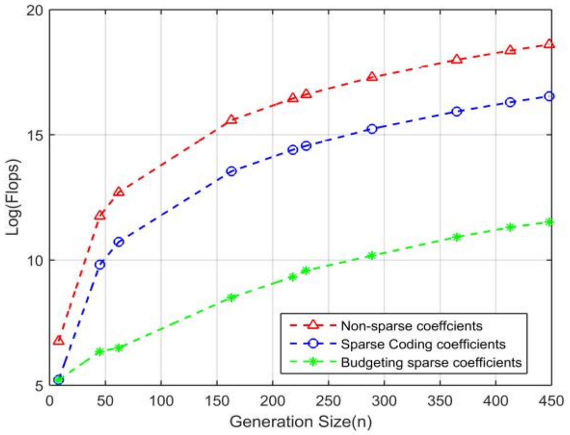

Fig. 2. Decoding Complexity for different scheme

B. *Security Analysis and Bandwidth Efficiency*

Lower triangular matrix with all elements one can be used for easy computation and better coefficient matrix generation method. But this raises the security issue to the information flow over the network. Receiving first encoded packet itself carries the information and if the second encoded packet could be received by the eavesdropper, by knowing first native packet from first encoded packet, second native packet can be decoded. So, the knowledge of encoding matrix and encoded packet may help wiretapper to extract the information from the packet tapped. To address this, randomness in coefficient matrix elements is to be added. By knowing the number of packet in particular generation (N) and state (K) of the pseudorandom generator $\emptyset(N, K)$, decoding matrix can be generated at receiving terminals by inversion of regenerated coding matrix with seeds received so only the transmission size of particular generation and state of the generator function in a particular transmission is enough to generate decoding matrix [α].

Simulation graph in fig. 3 and fig. 4, demonstrate the windowing effect in a single generation of packets. According to graphs, it can be summarized that windowing has not regular effects in computational complexity rather smaller windowing has better performance on smaller generation of size and vice-versa for the larger windowing. Theoretical analysis and computational simulation shown in the graphs demonstrated the gain of network coding with different number of parent packets in network coding scheme; however, error in a decoding of one packet introduced the error in the following packet decoding in receiver side. This is not scope of this research work; separate theoretical and experimental studies are going on error correction capabilities of network coding. There is no systematic ways to divide the packets into sub-generation; so, complexity has been studied against the different sub-generation sizes. Complexity reduction capability is understood from equation (3) as square of 20 (20^2) much higher than 20 packets sub-divided into 5 times 4X4 matrices (that is computational complexity of 5 times of order 4^2).

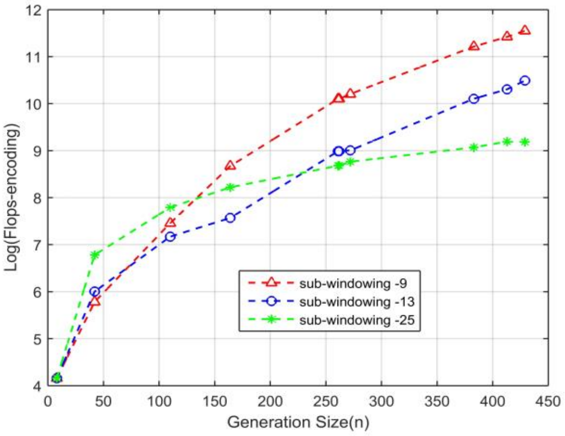

Fig. 3. Windowing performance in encoding

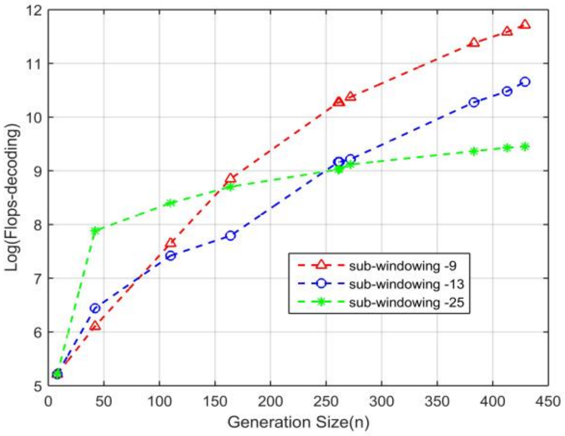

Fig. 4. Windowing performance in decoding

VI. CONCLUSION

Since sparseness to the coefficient matrix elements reduces the computational complexity of finding solutions for system of linear equations, introduction of sparseness to network coding coefficients reduces the computational complexity during the encoding process at sending nodes and decoding process at receiving nodes. Some known sparseness to coding coefficients can be introduced to an appropriate algorithm to solve the system of linear equations which is much faster and requires less memory storages. Lower triangular coding coefficient matrix adds benefits of computing native packets as soon as it starts receiving encoded packets at receiving nodes which has significant applications in video streaming with different video quality. Further division of a generation of level (n) into sub-generation with window size of lesser than n has better performance on decoding process. The windowing size is determined by the computational resources available in receiving devices which might reduce the upper bound given by max-flow min-cut theory for channel capacity rather tunes the computational power of the receiving terminals. It can also be concluded that varying window size has better performance than fixed windowing such as smaller windowing has better performance at lower generation size and vice-versa for larger windowing.

VII. CHALLENGES

Some trade-off is needed to be done between security and computational complexity. For enhanced security measures, higher cost is to be paid for computational complexity. Also, we can pay cost in bandwidth and some computation for enhanced security with continuous updates in coding coefficient matrix. Still, computation of sparser coding coefficient matrix is challenging to reduce computational complexity, enhanced security and reduced bandwidth at the same time. If the cost for computational complexity is to be reduced, then some trade-off is to be done for security issue. If computational complexity for coding and decoding process is to be reduced, then cost is to be paid for the security. Computation of coding coefficients for multi-hop network structure is another challenge and for dynamic network structures where number of nodes in a network is varying within small time period.

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