

Data Envelopment Analysis: Efficient Technique for Measuring Performance of Wireless Network Coding Protocols

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Abstract—Performance of network coding protocols have been largely evaluated using metrics such as packet delivery ratio and routing load, which can only determined how effective a protocol is. We describe the process of routing information in wireless network based on network coding and evaluate the efficiency of throughput benefits that network coding offers. This is archived with a specialized method known as data envelopment analysis (DEA). As a result, efficiency of COPE performance is compared with the traditional IEEE802.11. In additional, decision making unit called DMUs of protocols are determined. This could assist network designer to better plan for optimum benefits. Simulation results show that for all network scenarios examined, COPE protocol performs better than IEEE802.11 in terms of network effectiveness but its performance in terms of network efficiency depends on both inputs and outputs values.

I. INTRODUCTION

Wireless applications, its usage together with broadband evolution has revolutionized how people live and conduct business. So it does not matter how and where wireless technologies are applied, the simple fact is that it has affected every aspect of everyday life [1]. Unfortunately, network design and its efficient performance are still difficult task, especially with the emerging wireless applications brought by next-generation networks infrastructure and convergence [2]. Effective performance of individual technology and their integration have largely reported without considering the impact when the resources used are factored. This paper provides a qualitative method that provides additional metric to wireless network design performance, and shows how to measure its benefits in terms of efficiency by relating the input entities with the output entities.

A simple model of efficiently performed system is presented by studying the wireless routing protocols. An opportunistic network coding scheme known as COPE is considered [3], [4]. The performance of COPE in terms of its effectiveness and efficiency is evaluated and compared with the traditional IEEE 802.11. This protocol is considered as the base reference for its popularity and wide consideration. Besides, many other wireless standards allow broadband wireless access such as

IEEE 802.16, IEEE 802.20 and IEEE 802.22 but IEEE 802.11 is by far most successfully till date. The original IEEE 802.11 is designed based on how effective a message is communicated over a shared medium. Many enhanced schemes were presented to improved on the effective communications but came with overheads.

Both IEEE 802.11 and COPE, which are coded packet protocols are broadcast medium. Further, the link layer is responsible for the reliability of the broadcast but the 802.11 specification only includes an acknowledgement, and thus unreliable [5], [6]. COPE improves on the reliability by allowing the neighboring nodes to overhear the broadcast and thus have a copy of the transmitted packet that can be reproduced in case of packet lost. Other scheme such as BEND has also presented improved scheme by devising a more reliable link-layer broadcast [7], [8]. It is important to note that most of these protocols are designed to improve upon the effectiveness of others. That is, they are mostly concern about the output results.

In this paper, we consider new metric of evaluating the performance of network coding protocols using the DEA method. This method is a quatitative approach that has the capability to exploit the inputs and outputs entities, and to determine their relative efficiency. Our proposed idea takes into consideration characterization of the inputs and outputs variables and determine both percentage efficiency and their relative efficiency. We argue that though a protocol say COPE may send data very effectively to meet a certain network desire or goal, which the network requires and eventually archive those desire or goal. For instance, meeting the minimum requirements, but if the overhead of doing this is five times the overhead of any comparable similar networks of say IEEE 802.11, then it has not been very efficient though it fulfilled the minimum requirements. It means that the resources used is more than necessary and consequently jeopardizes the realizable benefits [9]. Different network scenarios will be drawn to present this argument. Further, using the DEA model, it will be shown that efficiency at different DMUs based on

certain inputs and outputs can be evaluated. Thus a network designer can make use of this opportunity to decide on what combination of DMUs to consider based on their relative efficiency. The results also provide opportunity to adaptively utilize two or more protocols in an efficient way. It is also an excellent approach to prioritize an application, for example, application that requires 100% efficiency may be given priority using the DMUs that archive such efficiency.

The remainder of the paper is presented in sections: section II presents the overview of wireless network routing protocols, section III describes the model, methodology and approach used. In section IV, performance evaluation are analyzed. Section V discusses the results, while section VI summarily concludes the paper.

II. OVERVIEW OF WIRELESS NETWORK ROUTING PRPTOCOLS

A. Network Coding: COPE Protocol

Network coding, which was introduced by Ahlswede et. al. [10] is a method by which intermediate nodes perform the mixing of information within the network. This results in the simultaneous use of communication links by multiple flows or packets. In traditional network system, the intermediate nodes can only store and forward a single packet one at a time to the next hop, because they were not equipped with the capability to mix packets. The simple technique in network coding operation is that each packet received by a node is combined with other received packets and then forwarded. This method of using a piggybacking scheme is presented by [13], and is illustrated in Figure 1. As shown, Alice's node sends packet *A* to Bob's node and Bob's node sends packet *B* to Alice's node. It is require that both Alice packet and Bob packet must first sent to the relay, *R*. The relay node then forwards each packet to the desire destination. If the relay is not equipped with the network coding capability, then the relay must send each packet individually using two time slots to make the total time slots equal 4 slots. If the relay is equipped with network coding, it will generate one encoded message, $A \oplus B$, and then broadcast the encoded packet to both Alice and Bob in a single time slots to reduce the total time slots to 3 slots. Given that both Alice and Bob nodes have their original packets, therefore, each can decode the message to extract packet sent.

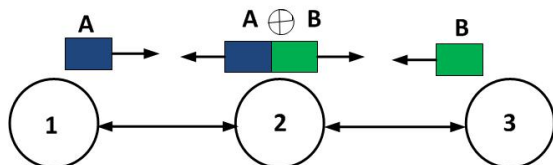


Fig. 1. Example of a network coding by linearly combining packets *A* and *B*, the relay can send two messages per unit time

Many researchers have improved on this idea [11], [12]. A significant work with practical approach and based on wireless network known as COPE is reported by Katti et.

al. [13]. Their work is design based on a simple heuristic coding scheme that operates over a finite field of size 2. It is capable of encoding and decoding packets at each hop. Hence, COPE tried to generalized the piggybacking scheme described above. COPE further exploits the broadcast nature of wireless medium by considering opportunistic listening and opportunistic coding techniques. With opportunistic listening, the wireless medium allows nodes to overhear packets transmission from their neighbors while opportunistic coding helps to maximize throughput by coding packets together.

However, in COPE, nodes do not wait for an optimal coding opportunity. For instance, node sends its packet at the first opportunity, that is, it does not necessarily need to wait for another codable packet in case it does not have more than one codable packet. Also, COPE is limited to field size of 2 whereas, it has been shown that sometimes, it is necessary to use higher field size to achieve the maximum throughput gains. Finally, COPE implementation is known to experience an encoding and a decoding issues.

B. Medium Access Control: IEEE 802.11 Protocol

IEEE 802.11 MAC is the main standard currently based on MAC protocol that defines two different access methods, the distributed coordination function (DCF) and the point coordination function (PCF). The PCF uses polling and scheduling and is optional while the DCF uses random access as the primary mode of operation and is designed based on carrier sense multiple access scheme with collision avoidance (CSMA/CA) [14], [15]. It is a basic access mechanism used in many applications such as ad hoc networks. The protocol requires a host to sense the medium before its intended transmissions. The host shelves the transmission for a moment whenever the channel is busy. The protocol is effective whenever there are less or no transmissions by other hosts. This is rarely possible because the channel is a share medium, and in practice, everyone wants to transmit. As a result, collision occurred. Collision is defined whenever two idle hosts sense the channel at a time and start to transmit simultaneously. In other to counteract this effect, a mechanism is designed for mobile node to sense the channel before each transmission, even if the channel is free, the host keeps sensing the channel for a specified time period to avoid any contender.

Another mechanism to resolve the collision and to address the hidden terminal problem is the use of virtual carrier sense (CS) mechanism. This requires every node to transmit a control packet called request-to-send (RTS) before the actual transmissions of the data packet. An RTS packet is packaged with the source address, destination address and the expected transmit delay of the data packet. In the same mechanism, the destination node replies with a control packet called clear-to-send (CTS) if the channel is free for transmission. The RTS/CTS combined scheme is a special handshake that its intention is to reserve the channel for transmitting the data packet. This signifies that other nodes have to delay their possible channel access whenever they overhear the RTS/CTS messages. The delay is estimated according to the

duration field in the RTS/CTS packets. Though this RTS/CTS handshake is an effective method for resolving the hidden terminal problem, but it also designed with an overhead, the duration field in the RTS/CTS packets provides the traffic load information around a mobile node.

Further, sometimes, the received packets are received in error. The destination node checks the error detection field in the received packet field and send an acknowledgment (ACK) packet to indicate that no error is found. Sometimes, it occurs that the sender nodes do not receive the ACK packet and this results into retransmission of the packet until an ACK is received or the number of retransmissions is over seven. This mechanism is an additional scheme to improve the performance of IEEE 802.11 but it also came with overhead.

III. MODEL, METHODOLOGY AND APPROACH

A. CCR Model

In this paper, Charnes, Cooper Rhodes known as CCR model is considered for the given input and output data. The data is classified to determine the efficiency of each DMU to be measured for optimization. Taking for example an n optimization, one for each DMU_k , which is designed to be evaluated. Then, a DMU_k can be denoted as trial DMU_0 with $1 \leq k \leq n$, further, the fractional programming, FP problem is solved such that

$$\begin{aligned} \max_{q,p} \Theta &= \frac{p_1 y_{10} + p_2 y_{20} + \dots + p_b y_{b0}}{q_1 x_{10} + q_2 x_{20} + \dots + q_a x_{a0}} \\ \text{subject to} \\ \frac{p_1 y_{1k} + \dots + p_b y_{bk}}{q_1 x_{1k} + \dots + q_a x_{ak}} &\leq 1 \quad (k = 1, \dots, n) \\ p_1, p_2, \dots, p_b &\geq 0 \\ q_1, q_2, \dots, q_a &\geq 0 \end{aligned} \quad (1)$$

where the values for the inputs are weights $q_i (i = 1, \dots, a)$ and the values for the output are weights $p_j (j = 1, \dots, b)$. The constraints imply that the ratio of output to input should not exceed 1 for every DMU . The objective is therefore to optimize both the input weight q_i and output weight p_i that maximizes the ratio of DMU that is considered. Therefore, the optimal value Θ^* is at most 1.

B. Linear programming Formulations

1) *The Primal Method:* The CCR Model based on primal approach is considered. With this method, fractional programming is transformed into a linear program. Hence, the notation is changed to LP and the optimization problem is given as:

$$\begin{aligned} \max_{\delta, q} \Theta &= \delta_1 y_{10} + \dots + \delta_b y_{b0} \\ \text{subject to} \\ q_1 x_{10} + \dots + q_a x_{a0} &= 1 \\ \delta_1 y_{1k} + \dots + \delta_b y_{bk} &\leq q_1 x_{1k} + \dots + q_a x_{ak} \\ &\quad (k = 1, \dots, n) \\ \delta_1, \delta_2, \dots, \delta_b &\geq 0 \\ q_1, q_2, \dots, q_a &\geq 0 \end{aligned} \quad (2)$$

The LP optimisation problem is solved by the *simplex method* of linear programming. This type of optimal solution is easily obtained by dealing with dual side of the LP [16], [17]. Therefore, simplex and dual methods are implemented in DEA to solve optimisation problems.

2) *Constant Return to Scale Method:* Other approach includes the return to scale but CCR model is built on the assumption of constant return to scale of activities and can be applied to the production frontier considering the fixed input and output [18]. A constant return to scale properties could be ascertained at a point on the frontier by considering optimal solution in its primal formulation.

C. DEA Approach

The network effectiveness using simulation approach is firstly evaluated, then the output results together with inputs values are characterized. These are then classified into inputs and outputs entities and piped into the DEA solver for execution and evaluation of network efficiency.

We consider measuring the efficiency of COPE and compare it with the IEEE 802.11 protocol. COPE is relatively a stable network coding protocol compared to other alternative protocols that were developed. In addition, it is widely considered as a reference protocol. Hence, COPE protocol is considered for the implementation. However, the approach can be easily extended to other network protocols to compare their network efficiency [9]. Generally, this approach is based on the DEA method that is discussed in the previous section.

Problem Formulation. *Supposing there is an optimal solution of LP that is represented by $(\Theta^*, q^*, \delta^*)$ where q^* and δ^* are values with some constraints. We can determine whether CCR-efficiency is achieved or not for different DMU s of COPE and IEEE 802.11 protocols.*

Hypotheses 1. *DMU_0 of COPE and IEEE 802.11 protocols is CCR-efficiency if $\Theta^* = 1$ and $\exists$ at least an optimal (q^*, δ^*) , with $q^* > 0$ and $\delta^* > 0$. Otherwise, DMU_0 is CCR-inefficient*

Hypotheses 2. *DMU_2 of COPE or IEEE 802.11 protocols is more CCR-efficient if its $\Theta_2^* > \Theta_1^*$ of another DMU_1 of COPE or IEEE 802.11 protocols*

While hypotheses 1 helps by given the relative important to each value and the relative contribution to the overall value of Θ^* in the evaluation of DMU_0 , hypotheses 2 compares their relative efficiency meaning that DMU of two or more entities can be related

IV. PERFORMANCE EVALUATION

A. Metrics

The following are the metrics that we considered:

Packet Delivery Fraction (PDF): This is the ratio of total number of packets that are successfully received at the destination nodes to the total number of packets that are sent by the source nodes within the simulation period.

Routing Load (RL): This is the ratio of total number of routing packets transmitted to total number of packets that actually received.

$$RL = \frac{\text{number of routing packets sent}(fd)}{\text{number of received packets}(R_x)}$$

Efficiency (e): To evaluate efficiency, DEA is employed. DEA is operation research technique based on relative efficiency measurement. It uses a linear programming approach, which is based on qualitative analytical measure to determine the efficiency of inputs and outputs of decision making units called *DMUs*. In this paper, four set of DMUs are evaluated to measure the performance of COPE and IEEE802.11 by relating their input(s) and output(s). The four *DMUs* considered represent different network nodes scenarios. In addition, the CCR model type, which has been discussed is considered. Input orientation with constant return to scale that is based on simple radial approach is also considered. For simplicity, one input entity with one output entity is implemented for the DEA model. The summary of the parameters used is presented in Table I. Further explanation on DEA framework is reported in [19].

Percentage Efficiency (%e): The %e is evaluated from the efficiency provided by the DEA. The conversion is staright forward.

Name	Value
Number of <i>DMUs</i>	4
Distance	Radial
Orientation	Input oriented
Returns to scale	Constant return to scale (CRS)
Model type	Single periodic model, CCR
Number of indices	2

TABLE I

DEA FRAMEWORK PARAMETERS FOR THE EVALUATION OF NETWORK EFFICIENCY

It should be noted that DEA requires the items to be considered classified into inputs and outputs. In order to simplify the work, the outputs results obtained from the simulation are classified. This is done because other parameters such as the number of received packets are already considered in the simulation. An important step is to observe the type of optimization the entities require. For example, we want to minimize the routing load and therefore classify it as input entity and we want to maximize the packet delivery fraction, hence it is classified as output entity. Then input orientation approach is suffice for this type of data. This implies that we want to minimize the packet delivery ratio why maintaining the packet delivery fraction. Output orientation may also be considered to obtain similar results. If that is consider, it implies that we want to maximize the packet delivery fraction why maintaining the routing load. Finally, CRS is considered in the implementation because of the nature of the data that was generated via simulation. The reason for

this approach is because the data value are subject to changes almost proportionally in such process as $\beta z_1, \beta z_2$, with $\beta > 0$.

B. Implementations

In order to evaluate the performance in term of network effectiveness, ns-2 [20], which is a packet-level simulator is used for the simulation that examined the COPEs performance in various wireless network scenarios. The performance is then compared with the traditional IEEE 802.11 protocol. It is implemented to find how effective they are in supporting multiple flows in multi-hop wireless networks. Different metrics are considered and the aggregate throughput gain of COPE is measured over 802.11. In the implementation, 5, 15, 25, and 35 mobile nodes are assumed to be randomly distributed within an area of 100×100 with fixed link rate of 1Mbps. Two-way ground propagation model and constant bit rate (CBR) with flow of packet size 512 byte are adopted. The simulation runs for eight time using different random seed numbers per scenario and the results are averaged over these runs.

# of Nodes	RL(Input)	PDF(Output)	%e	DMU
5	2,77394253790902	0,48355041003377	100	DMU1
15	3,02021002575788	0,38156223539373	72,5	DMU2
25	3,89877300613497	0,29880843263061	44	DMU3
35	2,98088779284834	0,40743531775936	74,5	DMU4

TABLE II

EVALUATED RESULTS FOR COPE PROTOCOL

# of Node	RL(Input)	PDF(Output)	%e	DMU
5	2,97507210548002	0,39237242237832	100	DMU1
15	3,51873638344227	0,2876029950813	62	DMU2
25	4,0475271411339	0,20920607681825	39,2	DMU3
35	3,24581724581725	0,27138416401802	63,4	DMU4

TABLE III

EVALUATED RESULTS FOR IEEE802.11 PROTOCOL

We evaluate the PDF and RL for COPE and IEEE802.11 protocols. The average value for the RL and the PDF for COPE is presented in column 2 and 3 of Table II respectively against the number of nodes in column 1. Similarly, the average value for the RL and the PDF for IEEE802.11 are presented in column 2 and 3 of Table III respectively against the number of mobile nodes in column 1.

In order to evaluate the performance in term of network efficiency, the outputs of the COPE and IEEE802.11 are considered, meaning that other metrics, PDF and RL are involved in determining the efficiency of the protocols. Further, they are characterized and classified based on DEA model requirements. The RL represents the input value into the DEA solver while the PDF represents the output value into the DEA solver as shown on Table II and III. The percentage efficiency and its corresponding DMUs are presented in column 4 an 5 of the two tables.

V. RESULTS AND DISCUSSIONS

The results presented in Tables II and III are plotted and shown in Figures 2 - 4. Figure 2 shows the result for the PDF that are obtained for different number of mobile nodes. It is observed that the COPE protocol outperformed the traditional IEEE802.11 in term of PDF measure. This means that the rate at which COPE is delivering packet is better than IEEE 802.11 protocol. This level of performance is attributed to COPE design in which a relay or intermediate node has capability to mix information and thereby improves the throughput. This has been proved and presented in many papers [21] - [23]. Therefore, it is not surprising to achieve such performance with COPE protocol.

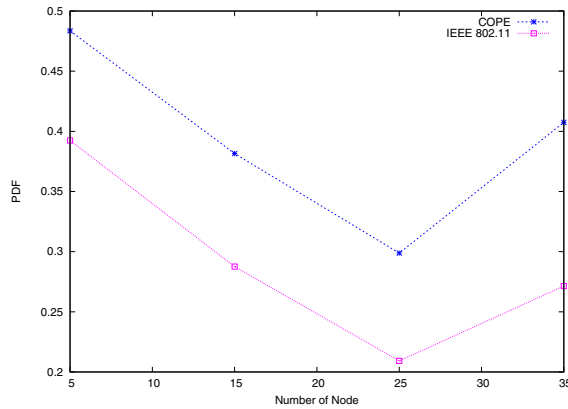


Fig. 2. Comparison of PGF performance for different number of nodes for COPE and IEEE 802.11 protocols

Figures 3 shows the results of RL metrics, which is another parameter to determine the performance of protocols. As observed, COPE protocol also performs better than IEEE 802.11 protocol in terms of RL measure. It means that IEEE802.11 design is associated with many overheads compared to COPE protocol. It is easy to point out that the mechanisms that is designed to address the hidden terminal problem in IEEE802.11, though effective but came with overhead. In addition, the ACK mechanisms to improve the reliability of the information exchange in IEEE802.11 is also a good scheme but the overhead can not be neglected especially when the sender node did not receive the ACK packet. This results into the retransmission of ACK until one is received. The overhead that is significant with COPE design has been the encoding and decoding complexity. This account for the reason why it has smaller routing load for all the mobile nodes examined compare to the traditional IEEE802.11.

The two metrics discussed above are functions of protocol effectiveness. They did not address the efficiency of the protocol. Figures 4 shows the percentage efficiency of the two protocols by relating all the metrics together including the inputs and outputs parameters. In order to determine the efficiency at an instance to help network designer make better decision, each protocol is classified based on its DMU, and the relative efficiency of each DMU of a proptocol is compared with the DMUs of other protocol. It is observed that from

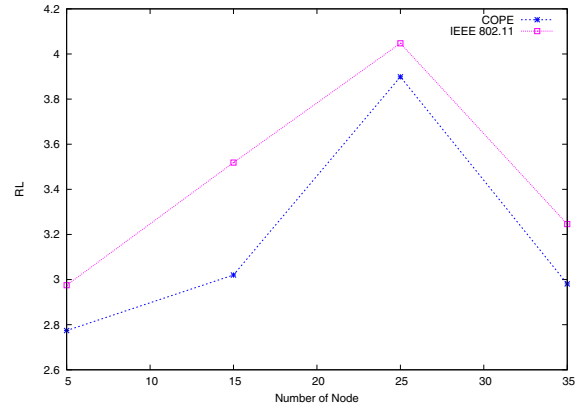


Fig. 3. Comparison of RL performance of different number of nodes for COPE and IEEE 802.11 protocols

Figures 4, the DMU1 of both protocols archived 100 percent efficiency and after that the DMUs of COPE performed better than the DMUs of IEEE802.11. Thus, we can generalized that COPE protocol is more efficient than IEEE802.11 but not in all cases. Therefore, it is difficult to conclude on the performance efficiency of a network until when the resources involved are considered.

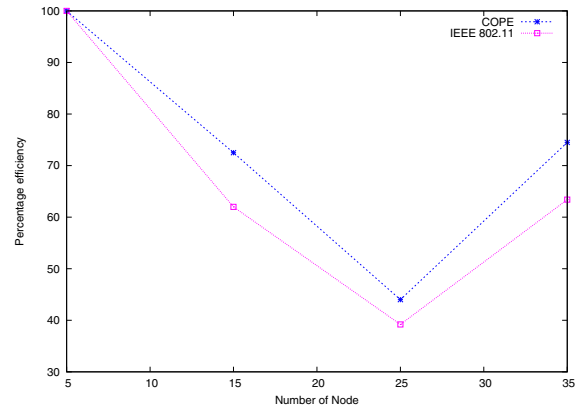


Fig. 4. Comparison of percentage efficiency of different number of nodes for COPE and IEEE 802.11 protocols

VI. CONCLUSION

This paper has approached the measurement of routing protocol using new metric that is based on DEA technique. The evaluation has considered the measure of efficient performance of COPE and IEEE 802.11, which are wireless network coding protocols. Simulation results show that metrics based on PDF and RL are not enough to determine the performance of network routing protocols especially when there is need for adequate and proper network management. In addition, adequate measure of networks can assist in the identification of importance network components such as node and links.

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