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Identification of Opportunities for Coding in a Network

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Abstract: *In wireless networks, throughput can be enhanced via network coding, which can also extend network lifespan in the case of devices running on battery, such as wireless sensor nodes. The number of transmissions needed for broadcasting a certain message over the network is also reduced through network coding, which thereby improves energy usage. On the other hand, network lifespan can be negatively impacted if network coding is applied too extensively.In addition to being expensive, network coding is associated with significant overhead as regards control message transmissions and can cause substantial delays. Hence, the performance advantages of network coding are somewhat diminished by its limitations. A key objective of the present study is to identify regions (i.e. nodes) that could benefit from network coding by undertaking network characterisation. Two aims are hoped to be achieved in this way, namely, prevalence of performance improvement over latency and overhead problems provided that a network is compatible with coding application, and the development of coding-aware routing protocols that can successfully direct packets within the network based on topology information.This study seeks to explore opportunities for coding at a node by creating a neighbourhood map for that node and extracting a graph (i.e. transformed graph) from that map. In theory, this should help to demonstrate that the transformed graph is the source of all potential coding opportunities. Furthermore, to identify every potential coding scenario for the node, an algorithm is generated as well. The coding capacity of every network node can be established in this way. Moreover, a range of topologies are used to assess the proposed approach. A valid suggestion is also made that coding gains at a node depend on the node degree and the edges amongst its neighbours.*

Index Terms: *Wireless networks, network coding, ad hoc networks, Throughput.*

I. INTRODUCTION

The form that inter-device communication takes nowadays has been markedly transformed by the technological innovations in wireless communication that have been recently accomplished. In addition to constructing networks independently, contemporary wireless devices can also share information with all network devices, thus helping one another. The two major parameters of particular significance for performance are latency and network lifespan. Throughput in wireless networks can be increased via network coding much more markedly compared to standard routing in wireless networks.

Figure 1.1 presents the concept underpinning network coding. In this representation, the same wireless environment [4] encompasses all nodes (A, B and C). If A and C want to share information, just one of them can undertake transmission at a specific moment because of channel restrictions. This process can be performed in the following way. Packets p1 and p2 are respectively sent by A and C to relay node B, which then forwards them to C and A, respectively. The number of transmissions required for this is four.

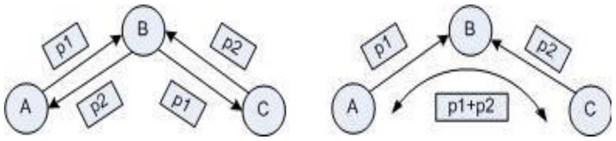

Figure 1.1: (a) without network coding; (b) with network coding

The number of transmissions can be diminished through the following scenario involving application of network coding. The central node B receives separate packets from A and C, amounting to two transmissions. The two packets are subjected to xor coding by B rather than being forwarded individually and the resulting combined packet is broadcasted in the common environment. The packets sent by them (i.e. p1 and p2) are known by A and C; thus, they can use the broadcast packet to apply xor coding to the known packet and extract the unknown packet. More specifically, A extracts p2 by undertaking the operation p1+ (p1+p2) upon reception of the combined packet. C extracts p1 in the same manner. This scenario reduces the number of four transmissions from the initial scenario to three. The manner in which network coding is applied in the above example, involving use of broadcast packet subject to xor coding (i.e. p1+p2) and the packets from the source nodes (i.e. p1 and p2) is known as opportunistic coding [4]. By contrast, when network coding entails achievement of higher savings by taking advantage of the common features of the broadcast wireless environment, it is referred to as opportunistic listening, which is described by the example below. In Figure 1.2, a single node is circumscribed by four border nodes, each of which transmits a different packet (p1, p2, p3, and p4, respectively). An assumption is made that the transmissions of B and D can be listened to by A as they represent A's neighbours on each side. The same goes for the other border nodes. A second assumption is that A and C, on the one hand, and B and D, on the other hand, have information to share with one another (p1 and p3 in the first case and p2 and p4 in the second case).

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The central node receives the messages transmitted by each border node and can send them all (p1+p2+p3+p4) in one transmission by combining them through application of xor coding. All destination nodes can employ the packets overheard from their neighbours to obtain the transmitted packet. For instance, alongside its own p3, C listened to the transmissions of B and D and thus obtained p2 and p4. To obtain p1, the packet intended for it, C must undertake the operation p2+p3+p4 (p1+p2+p3+p4). Owing to the opportunistic listening of network nodes, this procedure diminishes the original number of eight transmissions to five.

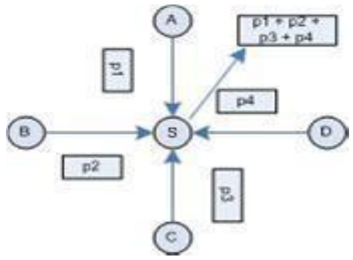

Figure 1.2: Opportunistic listening in wireless networks

1.2 Identification of network coding regions

Overhead associated with control message routing and unlimited latency in packet transmissions [10] are the main shortcomings of network coding. To identify the network regions most compatible with network coding, a strategy is proposed in this study to provide a precise determination of the coding capacity possessed by every network node. By integrating this information in the routing scheme design, the network can be made to perform better.Network deployment of wireless nodes is usually arbitrary in the majority of practical applications. The network coding opportunities of a node compared to other nodes depend on where that node is located in the network, how close it is to other nodes, the characteristics of its neighbourhood, and capacity for idle listening. This study seeks to determine the nodes most likely to implement network coding based on a proposed algorithm. The generated results and analysis point to the fact that there is a close relationship between coding gains at a node and factors like node degree and number of edges between its neighbours. The manner in which each factor affects coding gains is outlined. The results obtained could facilitate the creation of lightweight approaches for determining a network node's coding possibilities and could also contribute to the development of routing algorithms of greater efficiency.

II. LITERATURE REVIEW

Extensive implementation of network coding to enhance network throughput has been the approach adopted by recent related studies [11-15]. For example, one study relied on network coding to increase network throughput at the MAC layer as much as possible [4]. To determine whether the packets should be coded at the relay or the central node, the study employed a protocol based on the known ETX metric. The conclusion drawn was that throughput could be effectively improved with network coding. Routing protocols for taking advantage of network coding opportunities as much as possible were proposed in [5], involving network flow routing to an area that could allow network coding. Despite the fact that throughput was enhanced in this manner, the network lifespan was adversely impacted, because the involved nodes were excessively loaded when high traffic volumes were concentrated in a small network area. In fact, the network could even collapse as a result of such a strategy, which consequently is incompatible with networks that have energy restrictions. A coding-aware routing protocol for multiple unicast sessions in a wireless mesh network was put forth in another study [6], with the purpose of enhancing throughput without disturbing the interference restrictions associated with channel capacities. A compromise was established between routing flows to benefit coding and preventing interference. The approach can be useful for networks without energy awareness, but it is not compatible with networks that have energy limitations and network lifespan is crucial.To attain throughput gains anticipated from network coding, MAC scheduling algorithms have been proposed in [8]. Previous research on network coding assumed that no upper limit existed on the number of packets that could be subjected to coding in just one transmission, and therefore the gains from network coding could be limitless. In reality, however, the efficiency with which opportunities can be detected by the coding scheme determines the benefits that network coding can supply. Limits on the throughput gains that could be derived from network coding were suggested by several studies [16-20]. Thus, a fixed upper limit for throughput gains in a wireless network was established in [16]. Meanwhile, limits on gains were placed according to the number of transmissions during application of network coding for improving energy usage in sensor networks [17]. The impact of realistic physical layer and medium access regulated by random access mechanisms on practical network coding performance was assessed in [18]. This helped to impose limits on the number of packets that a node could encode in one transmission.

III. USE OF GRAPH TRANSFORMATION FOR CODING REGION IDENTIFICATION

Possibilities for coding at a node can be identified based on a process and algorithm employing a graph transformation of that node's neighbourhood map [24]. The first step is the conversion of the node and its single-hop neighbours into that node's neighbourhood map, known as neighbourhood graph, which is unique to the node. The set of edges associated with the graph comprises the edges between the node and its neighbours as well as the edges between any two of the node's neighbours. The neighbourhood graph (G_x) for the chosen node x constitutes the focus in the following part. Identification of the coding possibilities requires conversion of the neighbourhood graph into a transformed graph.

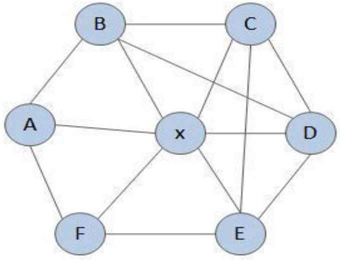

Figure 3.1: Neighbourhood graph ($G_x(V_x; E_x)$)

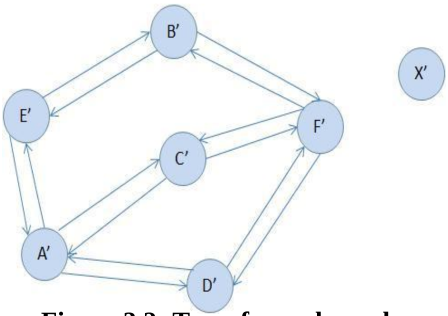

Figure 3.2: Transformed graph

Graph transformation: If the neighbourhood graph of node x is $G_x(V_x, E_x)$, then a transformed graph $X(V_x{'}, E_x{'})$ can be derived in the following way. The sets of nodes $V_x{'}$ and V_x are identical and the node in graph X equivalent with node v ∈ V_x in $G_x$is node v ∈ V_x. The form taken by the edge set of X is $E^1{}_{x=}$ $\{(u^{1,}$ v1$),\forall u^1,v^1\in v^1x\}-E_x$. A division of the undirected edge (u, v) $\in E_x$into bidirectional edges u→v and v→u is possible, enabling identification of the edge set of $E_x{'}$. In this manner, edges absent in G_x can be found in X and the other way around.

Definition 1: The number of packets that a central node can code and broadcast throughout the network in just one transmission is determined by the coding number.

Definition 2: The overall number of potential coding combinations at a node is determined by coding groups.

Theorem 1: The transformed graph provides the coding groups for coding number ≤ n[N(u)].

The node degree of neighbours determines the coding possibilities at a node. This corresponds to the maximum of (total size- node degree $(u'))\forall u' \in V$ in the case of the transformed graph.

The transformed graph helps to identify the coding groups for coding number two. However, additional coding possibilities cannot be gauged based on this correlation.

The conditions required for a receiving node to effectively extract the targeted packet are verified by the central node. Regarding the transformed graph, several conditions must be closely complied with when a coding number higher than two is selected. It is assumed that the edge (u',v') and path $P_{u\to x\to v}$ in $G_x$are correlated.No edge should be formed by vertex u (as tail) with a node that fronts the selected edge. Likewise, no connection should be formed between v (as head) and a vertex representing the tail of the selected edge.

IV. ALGORITHM FOR IDENTIFICATION OF NETWORK CODING OPPORTUNITIES

4.1 Algorithm

The identification of a node's coding possibilities based on graph conversion of the node's neighbourhood map has been addressed in the preceding section. The algorithm based on which a node can be ranked within the network according to the coding ratio is the focus of the current section.

The notations associated with algorithm characterisation are provided below.

Paths chosen for coding are encompassed in P(i), with the coding number higher than two being indicated by i.

Edges in $E_x{'}$ that can be chosen for coding are incorporated in H.

Coding possibilities at a node can be identified based on the methodology supplied by the algorithm. More specifically, the coding capacity of a node is indicated by that node's rank. Usually, the frequency and efficiency of packet coding are greater in the case of nodes of high rank compared to those of lower rank. The process through which a network node's coding capacity can be assessed is outlined by the algorithm in Figure 4.1. Thus, scenarios for coding number two are delineated based on the procedure described by steps 1-7. After selection of one edge e, the remaining edges are subjected to scanning to determine their viability for coding. K is the set under consideration. As shown in steps 3 and 4, a single edge from $E_x{'}$ is selected in every iteration, while the edges sharing vertices are eliminated from K. In step 4, edges incident on receiving capable nodes are eliminated as well. The edges associated with paths that the central node x can code are attached to set P(2) upon completion of every iteration. Steps 8-12 explain a similar procedure for coding number higher than two. Since i packets coding scenarios represent i-1 flows and an extra flow, P(i – 1) must be used as input to determine the potential combinations for coding number i. An element a is selected in step 8 and this element lacks the edges in $E_x{'}$ that are present in set K. In keeping with steps 3 and 4, edges equivalent with every edge in a should be eliminated from K. Following step 12, i edges present in an element a∈ P (i) are equivalent to paths in the initial graph that the central node can code. A node is ranked according to the number of entries in P (i) ∀ i > 2. The allocation of ranking is relative within the network. In the network presented in Figure 4.5a, four is the highest coding ratio possible because the degree of node x is four. Figure 4.5b illustrates the transformed graph of x. Combinations may not happen in identical proportions, regardless of whether the coding ratio of a node is high. This may be attributed to the reduced traffic routed via the node or lack of complement flows for combined coding and transmission. Node mobility causes modifications in network topology. A node's coding pattern is influenced by all these variables. A network's dynamic behaviour is disregarded in this study.

Algorithm

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For coding number $i = 2$
STEP 1: $H = E_x{'}$.
STEP 2: Selection of edge e, with $e = (u, v) \in H$. $K = H-\{e\}$
STEP 3: Edges derived from u should be eliminated from K
STEP 4: Edges incident on v should be removed from K
STEP 5: $P (2) = \{e, e_{i\}}, \forall e_i \in K$.
STEP 6: $H = H-\{e\}$.
STEP 7: steps 2-6 should be iterated until H is empty and both packet coding scenarios at central node are included in set P(2)
For coding number $i > 2$
STEP 8: An element $a \in P (i- 1)$ should be chosen and every combination for coding number i-1 is included in the set P(i-1)
STEP 9: $K = E_x{'} - \{e_{i\}} \forall e_i \in a$.
STEP 10: Edge $(u'; v')$ should be eliminated from K,either $(u', x') \in E_x{'}$ and $(w', x') \in a$. or $(y', v') \in E_x{'}$ and $(y', g') \in a$.
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STEP 11: $P(i) = \{a, e_{i}\}, \forall e_i \in K$.

STEP 12: Steps 8-11 should be iterated until selection of every element in P(i-1) is completed

Figure 4.1: Algorithm for identification of coding possibilities at the central node

V. SIMULATION RESULTS

Experiments have been conducted in this study to assess how well the suggested algorithm performed with regard to identification of network coding regions. To this end, the network topologies shown in Figures 5.1a and 5.2a were taken into account, each respectively representing a segment of the university network with 24 nodes and a 14-node spin topology. The nodes in the networks presented in the two figures can code more than one packet in one transmission. However, not all the nodes have the same coding ratio. In the graph, the nodes with comparable coding ratio are clustered together, ranked the same and highlighted in the same colour.

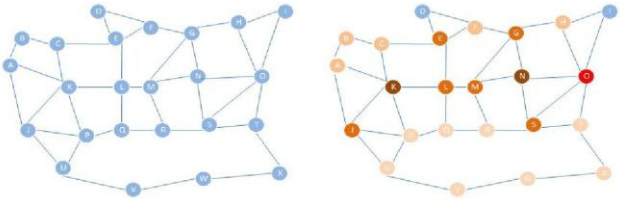

Figure 5.1: a) ISU network; b) labelled nodes within the network

The number of nodes in each group is indicated by the results in Figure 5.3 in contrast to the coding ratio associated with the network in Figure 5.1a. Coding opportunities increase with the elevation in a node's rank.

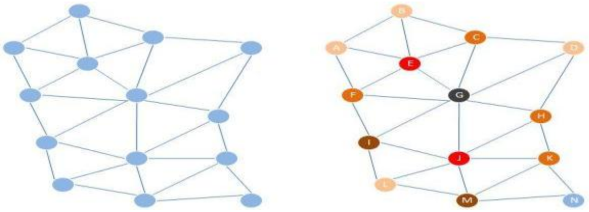

Figure 5.2: a) spin network; b) labelled nodes within the network

Neighbourhood graph and degree are similar in the case of nodes of the same rank, as can be seen from the topology. For instance, compared to the other network nodes, the coding ratio of nodes O, K and N is higher. Likewise, these nodes have a high degree and most of their neighbours are linked. Aside from opportunistic coding, the coding gains from opportunistic listening are enhanced by the fact that the neighbours are directly connected.

The results shown in Figure 5.4 permit comparable observations. In this network, the gain associated with opportunistic listening prevails, and therefore this topology has better compatibility with coding. For instance, in the case of nodes E and J, connectivity exists between the majority of their neighbours, which means that more packets can be coded in one transmission. Node G is a similar case; this node has a higher coding ratio than the other network nodes due to its high degree.

Due to the fact that graphs with full connectivity are created by the neighbourhood graphs of nodes D and I (Figure 5.1b) and node N (Figure 5.2b), the present scheme does not provide ranking for these nodes. Hence, in a standard scenario, they are not selected as intermediary.

5.2. Experimental Setup 2

As indicated by the above results, the identification of coding possibilities at a node is heavily dependent on node degree and inter-neighbour edges. Coding gains with diminished transmission overheads could be obtained by employing these network statistics as a metric in current routing protocols.

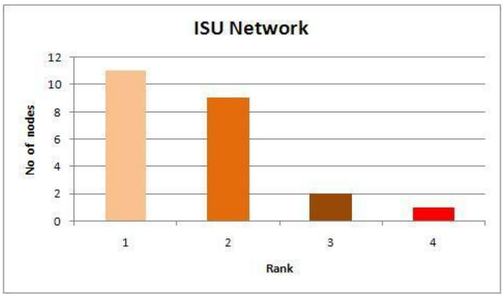

Figure 5.3: Comparison of ranks and number of nodes in the ISU network

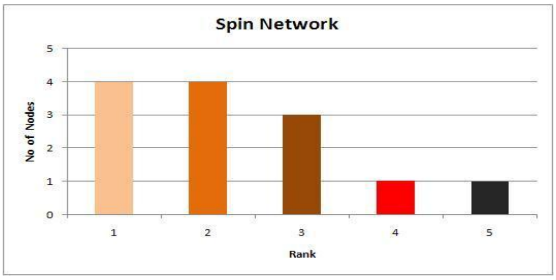

Figure 5.4: Comparison of ranks and number of nodes in the spin network

A number of one hundred connected network topologies with 20 nodes and 50 links were produced arbitrarily with the aim of showing how coding opportunities were correlated with the above-mentioned factors.

For every node in the graphs, node degree and the level of connectivity between neighbouring node pairs (edges linking adjacent nodes) were determined. The results of the simulation regarding the experimental data related to coding possibilities were contrasted against the two factors.Based on the above observations, a lightweight strategy for accurately identifying coding clusters in a network can be formulated. Effective coding-aware routing algorithms can be developed by employing this metric to design distributed protocols. Consequently, the extra overhead that accompanies enhancement of network coding gains can be diminished.As previously demonstrated, node degree and neighbour connectivity have a significant impact on a node's coding degree. All nodes receive this input during their configuration in the network. These factors form the basis of the heuristic approach suggested in this study for use in the identification of a node's coding degree and demonstration of how such information could support performance of routing.

VI. CONCLUSION

To assess the coding opportunities at a node, this study has also generated a neighbourhood map and transformed graph for that node. It was demonstrated that, in theory, all potential coding opportunities at a node can be extracted by the transformed graph. Furthermore, to establish the coding number of every network node, a specific algorithm was designed as well. Various topologies were used to assess the suggested approach. Results revealed that the coding ratio of nodes with the same topology was similar. For instance, due to network configuration, the topology in Figure 5.2 is more compatible with coding compared to the topology shown in Arbitrary topologies were also used to assess the proposed algorithm and in this way it was found that coding ratio and node degree were correlated, as were the coding ratio and the number of edges between a node’s neighbours. The node degree and the number of edges between a node’s neighbours influenced the level of correlation. Additionally, a surprising result was obtained, namely, that greater coding gains were achieved due to fewer edges between neighbours when the node degree was reduced. Establishing the advantages of network coding implementation for a network was the overall aim of the present study. The compromise between obtained gains and extra overhead can be assessed based on the findings of this study. The lightweight solution can be applied to develop distributed routing protocols and therefore to achieve an improved throughput and extended network lifespan. The extent to which coding degree is influenced by the dynamic behaviour of a network will form the focus of a future study.

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