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Network Coding-aware Routing for Energy Minimization in Wireless Ad-Hoc Networks

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Abstract

Throughput in wireless networks can be enhanced with the help of network coding. This approach also increases network lifetime in the cases of devices running on battery, such as wireless sensor nodes. Additionally, network coding achieves a reduction in the number of transmissions needed for transmission of a specific message through the network by making energy usage more efficient. Despite its benefits, however, network coding can have a negative impact on network lifetime if it is implemented excessively. The present study addresses this compromise that demonstrates that networks with energy restrictions are incompatible with the current network coding strategies based on throughput. One routing issue is attributed particular importance, namely, reduction of overall energy usage and improvement of individual node lifetime through effective routing of a series of traffic demands over the network.A range of analytical formulations are put forth to generate an optimal solution for the issue of multi-path routing. Results show that, by comparison to solutions without network coding, the suggested solution improves energy efficiency while at the same time satisfying the specified lifetime restrictions.

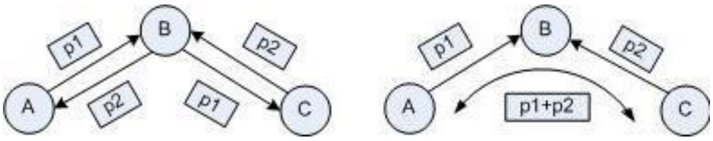
Keywords: Wireless ad hoc networks, Routing, Network coding, Energy Minimization

1. INTRODUCTION

The form that interdevice 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 major parameters of particular significance for performance are throughput, latency and network lifetime.

By comparison to normal routing in wireless networks, throughput is significantly increased in such network by the approach of network coding.

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.



(a) (b)

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

The number of transmissions can be reduced 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, each of the four border nodes circumscribing one node transmits a distinct packet (p1, p2, p3, and p4, respectively). An assumption is made that, since B and D represent A’s neighbours on each side, their transmissions can be listened to by A. The same applies to the rest of the border nodes. It is also assumed that A wants to share p1 with C and C wants to share p3 with A, while B wants to share p2 with D and D wants to share p4 with B. By combining the messages received from each border node through application of xor coding, the central node can send them all (p1+p2+p3+p4) in one transmission. The packets overheard from their neighbours enable the destination nodes to extract the transmitted packet. This means that C obtains p2 and p4 from B and D, respectively, in addition to its own p3. Subsequently, C must undertake the operation p2+p3+p4 (p1+p2+p3+p4) to extract p1, the packet meant for it. Because of opportunistic listening of network nodes, the original number of eight transmissions can be diminished through this procedure to five.

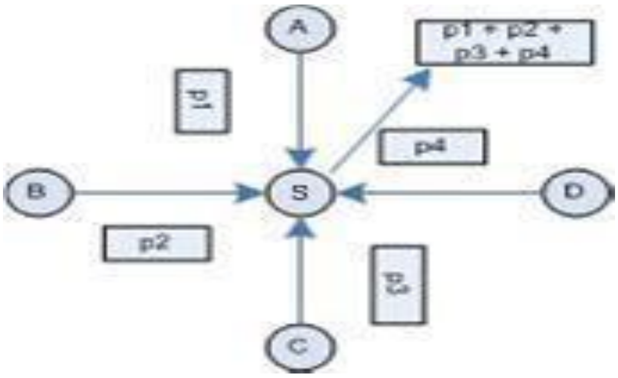


Figure 1.2: Opportunistic listening in wireless networks

The process undertaken in this study involves implementation of network coding at the routing layer with the purpose of reducing energy use and examination of the associated trade-offs. A number of challenges arise when network coding is applied to networks with energy restrictions, which also highlights the comprise that occurs between overall energy reduction and network lifetime. Network hot spots form when traffic is routed to enable network coding and achieve the goal of improving energy efficiency. The network lifetime is adversely affected by such hot spots.As far as the author is aware, no other study has adopted such an approach of saving energy by implementing network coding and examining the compromise between overall energy reduction and network lifetime by focusing on the multi-path routing problem in a static way.

2. REVIEW OF LITERATURE

Extensive implementation of network coding to enhance network throughput has been the approach adopted by recent related studies [4-15]. For example, one study sought to increase network throughput at the MAC layer as much as possible through network coding [4]. To determine whether packet coding should occur at the relay or the central node, a protocol based on the known ETX metric was employed. Results indicated that throughput improvement could be effectively achieved with network coding. Directing of network flow to a region where network coding was permitted was the concept underpinning the routing protocols proposed in [5] to take advantage of network coding opportunities as much as possible. However, due to the excessive load placed on the involved nodes as a result of concentration of high volumes of traffic in a limited network region, the network lifetime was negatively affected, even though the throughput was enhanced. In fact, the network could even break down due to such an approach, which therefore is inapplicable in the case of networks with energy limitations.

To improve throughput while maintaining the interference restrictions related to channel capacities, a coding-aware routing protocol for multiple unicast sessions in a wireless mesh network was suggested in [6]. To benefit coding and prevent disruption, a compromise was made between routing flows. The approach is inapplicable to networks with energy restrictions and high significance attributed to network lifetime, but it can benefit networks without energy awareness.To obtain the throughput gains that network coding is expected to generate, one study proposed MAC scheduling algorithms [8]. In prior studies, it was assumed that coding could be applied to a limitless number of packets in a single transmission, meaning that network coding gains could be limitless as well. In reality, however, the effectiveness with which the coding mechanism can detect opportunities determines the advantages that can be derived from network coding.

Bounds on the throughput gains that network coding could provide were suggested by a number of studies [16-18]. Thus, one study implemented a fixed upper limit for throughput gains in a wireless network [16]. To reduce energy consumption in sensor networks, a different study imposed limits on gains in keeping with the number of transmissions during network coding implementation [17]. Yet another study evaluated the effect of realistic physical layer and medium access regulated by random access mechanisms on practical network coding performance [18]. In this manner, the number of packets that a node could encode in a single transmission was bounded.

3. ENERGY-AWARE NETWORK CODING

3.1 System Model Description

The working assumption is that network topology does not change and a base station that determines paths according to demanded connections keeps track of every node. In this context, a node with high energy level and constant power source is established as the base station. In the present case, since the number of packets that a node can receive is unaffected by network coding implementation, the energy consumed by packet reception is considered to be insignificant and is nearly equivalent to a case without network coding. Furthermore, by comparison to packet transmission, packet reception is associated with a considerably lower level of energy usage. In terms of node energy or functionality, no assumption of uniformity is made in the proposed model. Although the battery power levels of the nodes can differ initially, it is considered that external battery devices are inaccessible to them upon mobilisation in the network.

According to the potential to split the flows, multi-path routing solutions are put forth by this study. In the case of the issue of multi-path routing, packets routed via different paths for identical flow may be delayed to different degrees and therefore may not be received by the destination node at the same time. It is presumed that such disarrayed packets can be managed by the destination node.

To achieve network coding, the transmitted packets are subjected to a straightforward XOR operation that does not consume a high level of energy. Therefore, the energy consumption associated with XOR is considered insignificant. XORed packets are differentiated from those not subjected to this operation through the addition of a header to a packet, which indicates the sequence number of the XORed packets. The receiving node can use this information to extract the unknown packet by choosing an appropriate packet from its buffer and subjecting it to XOR with the received packet. A scenario with just two XORed packets is considered to avoid complicating the model unnecessarily. A future study could employ a larger number of XORed packets and explore the additional gains derived from them.

The energy used to transmit a certain amount of information in a network with energy restrictions can be diminished through implementation of network coding. In current coding-aware routing protocols, all traffic is directed towards those network areas where combined packet coding is most likely to be possible. Hence, the traffic load is excessive at some key network nodes, whereas the rest are inactive. Network coding involves high energy consumption and therefore the key nodes die faster than the inactive nodes. The disrupted residual energy balance that is thus created may diminish the network lifetime, despite the fact that most nodes have not died and possess high energy supplies.

3.2 Application of network coding for improved energy efficiency

In the following part, lifetime restrictions will be applied to the network and the overall energy used by all network nodes will be reduced. The issue is outlined below.The traffic volume on every path is measured for a given traffic matrix and series of routes for every pair of source and destination nodes in order to reduce overall energy consumption in accordance with lifetime restrictions during application of network coding.The proposed model makes use of multi-path routing. The issue of reduction of overall energy usage according to lifetime restrictions can take the form of a linear programming (LP) problem.The reduction of the overall energy used by every node during traffic routing is the goal of the above linear program. The term is equivalent to the totality of flow values for all demands in which node b occurs in the flow-selected path.Flow constraint: The equivalence between the totality of flow values for demand i routed via more than one path and the traffic volume intended for routing for the i^{th} demand is guaranteed.Broadcast traffic constraint: The coded traffic is known as broadcast traffic.Unicast traffic constraint: The non-coded traffic whose forwarding is link-based is known as unicast traffic. Unicast and broadcast are the types of traffic that can be routed via a link.Capacity constraint: The guarantee that transmissions with a common medium do not occur at the same time at the MAC layer is provided by the capacity constraint.Lifetime constraint: The improvement of energy efficiency is the aim of network coding opportunities for a specific traffic load, and for this purpose, demands are routed aggressively. To prevent network breakdown, a minimum necessary network lifetime is imposed by the lifetime constraint for every separate node. It can be said that achievement of homogeneous distribution of residual energy over the network nodes is the purpose of the lifetime constraint. No network node suffers full battery power depletion due to the minimum residual energy condition that is imposed. Consequently, the network can support traffic demands for longer as its lifetime is extended

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3.3 Performance Evaluation

3.3.1 Experimental Setup

Different traffic and channel capacity conditions have been used to assess the suggested models and observe how they performed in relation to one another. A 10*10-sized grid topology with unit normalised distance between neighbouring nodes formed the basis for the assessment of the proposed model. The reason why the grid topology was selected is that, by contrast other general topologies, it provides better possibilities for network coding and therefore it facilitates the assessment of network coding and related trade-offs. Source and destination nodes were selected arbitrarily to produce twenty traffic demands for every assessment iteration.A comparison of the relative performance of energy minimisation with network coding (EMC) and energy minimisation with lifetime constraint (EMCL) was conducted based on measurement of the normalised overall energy usage, which was normalised in terms of the scenario without coding and demand routing through shortest path, and the mean standard deviation. A lifetime constraint was identified in relation to the EMCL but not EMC.

For the purposes of the assessment, several parameters were varied, as follows:

- Channel capacity factor: This parameter represents the ratio between channel capacity and overall network demand traffic.
- Traffic load factor: This parameter is the ratio between the overall demand traffic and channel capacity. When each of these factors is varied, the other one is maintained constant.
- Lifetime constraint

3.3.2 Results

The correlation between channel capacity and energy usage

The relative performance of EMC and EMCL is compared with the scenario without network coding in Figure 1.3 The volume of traffic that can be transmitted through the same path is greater and at the same time the MAC constraints are uphold, owing to the expansion of channel capacity for a specific traffic load. To put it differently, there are greater possibilities of network coding when the channel capacity factor is increased, while normalised energy usage diminishes for every scenario. However, energy decrease stops after a certain threshold of channel capacity enhancement in the case of EMCL. The reason for this is that the volume of traffic that can be directed through each network path is limited by the lifetime constraints applied to each node. These constraints are higher in EMCL, which means that this trend is especially visible in that scenario. Furthermore, once every possibility for network coding has been exhausted, the EMC curve displays stability.

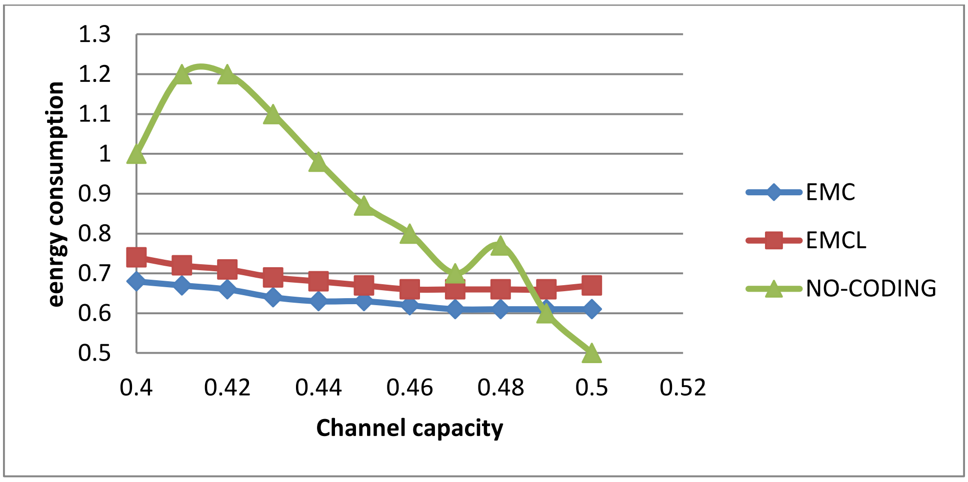

Figure 1.3. The impact of channel capacity on energy usage

The correlation between traffic load factor and energy usage

The traffic factor is varied in Figure 1.4 to permit comparison of the relative performance of EMC and EMCL. At first, the greater availability of traffic for improved performance of traffic mixing when the traffic load is augmented for a specific channel capacity results in more possibilities for network coding. However, the augmented workload leads to an energy usage increase that exceeds the level of energy decrease as a result of network coding when the traffic is intensified even more. Therefore, the normalised energy usage of both schemes is elevated after the 0.6 traffic factor. Nevertheless, the figure indicates that the EMC and EMCL perform better than the scenario without network coding.

The correlation between lifetime constraint and energy usage

A comparison of the relative performance of the no coding and EMCL in terms of lifetime constraint is provided in Figure 1.5 Thus, restrictions are imposed on the traffic to spread out more when the lifetime is expanded. Consequently, there are fewer opportunities for network coding and therefore, energy savings decrease. Nonetheless, by comparison to the scenario without network coding, both EMC and EMCL present considerable reduction of energy usage.

The correlation between traffic factor and residual energy

The manner in which the traffic factor influences the rest of the energy values of separate network nodes is illustrated in Figure 1.6 The extremely high energy value displayed by EMC points to a heterogeneous distribution of the residual energies between separate nodes following the management of the given traffic. Both schemes present a reduction in energy due to the fact that the spread of the traffic becomes broader with the intensification in traffic.

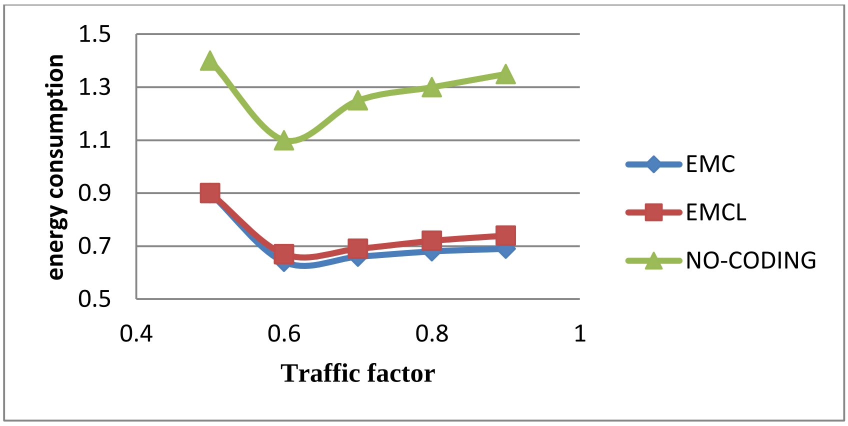

Figure 1.4. The impact of traffic factor on energy usage

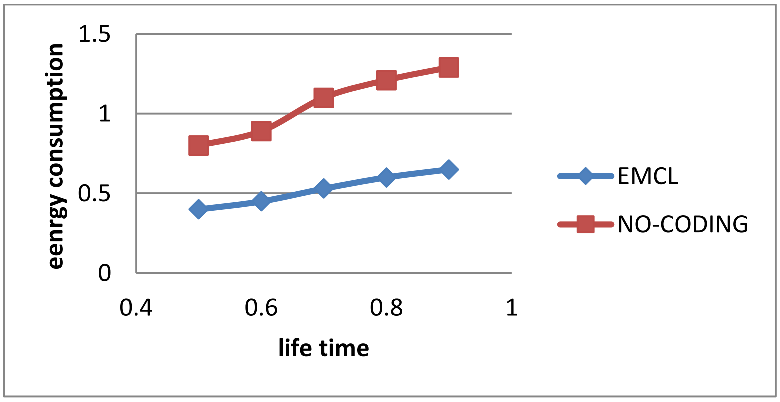

Figure 1.5. The impact of lifetime constraint on energy usage

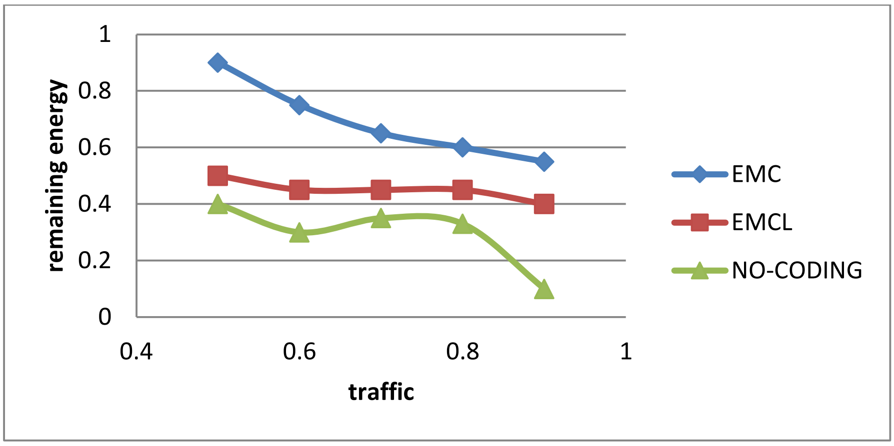

Figure 1.6. The impact of the traffic factor on the residual energy

All in all, the best distribution of residual energy is accomplished by EMCL because it attempts to satisfy lifetime constraints by spreading the traffic over the network.

The correlation between channel capacity factor and residual energy

The channel capacity for a specific traffic is varied in Figure 1.7 to enable comparison of how residual energy is distributed in the EMC and EMCL schemes. The greater space for the routing of the traffic through one path to generate higher coding gains is made possible by the increase in channel capacity, which provides more possibilities for network coding.

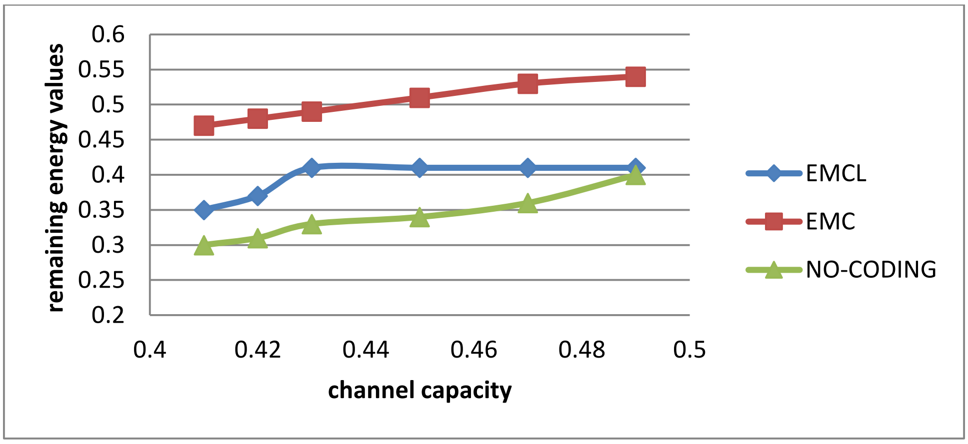

Figure 1.7. The impact of channel capacity on residual energy

However, the traffic distribution becomes more uneven and the residual energy values increase. Nonetheless, the unevenness of the traffic load distribution is halted due to energy constraints that determine the stabilisation of the EMCL scheme as the traffic is further intensified. Overall, by comparison to EMC, the EMCL schemes presents better values of residual energy.

4. CONCLUSIONS AND FUTURE WORK

In wireless networks, application of network coding can reduce energy consumption and increase throughput. The method of network coding was initially intended for throughput maximisation, but the present study has demonstrated that it is also a useful approach for reducing energy consumption by decreasing the number of transmissions required for packet broadcasting in a wireless network. The study has paid particular attention to the trade-off between selection of paths compatible with network coding and network lifetime. The extensive application of network coding has a negative impact on network lifetime because it leads to the formation of hot spots where nodes die, which causes network disconnection.

To this end, the transmission energy consumed by shortest path routing was compared with the results of LP, of which the EMC scheme applied network coding extensively while the EMCL scheme made sure that every node kept a certain portion of its energy to guarantee network lifetime. By contrast to the shortest path routing, both schemes reduced energy consumption. Due to traffic distribution between a greater number of paths, the energy reduction associated with network lifetime guarantee was somewhat lower while the distribution of the residual energy was more homogeneous.The overarching purpose of the present study was to assess the benefits of network coding implementation. The trade-off between gains attained and extra overhead generated can be appraised based on the results obtained. The present light-weight approach for improved throughput and lifetime can be employed to develop distributed routing protocols. Future work will address the issue of how the coding degree is influenced by the network’s dynamic behaviour.

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