

Energy Minimization through Network Coding for Lifetime Constrained Wireless Networks

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Abstract—Energy management is the key issue in the design and operation of wireless network applications like sensor networks, pervasive computing and ubiquitous computing where the network is primarily driven by battery-powered embedded devices. This paper studies network coding as an energy minimization technique. Network coding reduces the energy consumption by minimizing the number of transmissions required to communicate a given amount of information across the network. However, aggressive application of network coding adversely affects the network lifetime. We illustrate this trade off in this paper, and show that the existing throughput based network coding approaches cannot be applied to energy-constrained networks. Specifically, we address the following routing problem. Given a set of traffic demands the goal is to route the demands across the network with the objective of minimizing the total energy consumption while providing guarantees on the lifetime of individual nodes. This paper studies multi-path variation of the above routing problem. We present analytical formulations to solve the problem optimally. Evaluation results indicate that the proposed solution is 35% more energy efficient than no-network-coding solution while still meeting required lifetime constraints.

I. INTRODUCTION

Recent technological advancements in wireless communications are fundamentally changing the manner by which devices communicate with one another. Modern wireless devices build networks on their own and aid each other in passing information to any device in the network. Many are battery powered, thus energy conservation is critical to maximizing their useful lifetime. We will show that network coding, a technique originally introduced to maximize throughput, can be used as a technique to save energy by minimizing the number of transmissions needed to deliver a set of packets.

The basic idea of network coding is illustrated in Fig. 1 where nodes A , B and C share the common wireless medium [1]. Consider a scenario where nodes A and C have information to exchange. Due to the channel constraints only one node can transmit at any given time. One possible way of accomplishing this information exchange is as follows. Node A sends its packet ($p1$) to relay node B . Node B forwards this packet to node C . Similarly, node C sends its packet ($p2$) to node B which in turn forwards it to node A as shown in the figure. This involves a total of four transmissions.

Now consider the scenario where network coding is applied to reduce the number of transmissions. Nodes A and C transmit packets to central node B sequentially (two transmissions).

Node B , instead of directly forwarding each packet to its destination, XOR's the two packets and broadcasts the result as a single packet in the shared medium as shown in the figure. Both nodes A and C know their own packet ($p1$ and $p2$, respectively) that originated from them. They can therefore retrieve the unknown packet by XORing the known packet with broadcast packet. For example, node A on receiving $p1 \oplus p2$ performs the operation $p1 \oplus (p1 \oplus p2)$ to obtain $p2$. Similarly, node C retrieves packet $p1$. This entire process takes exactly three transmissions as opposed to four transmissions as discussed above. In a simplistic model this technique will result in 25% less energy consumption.

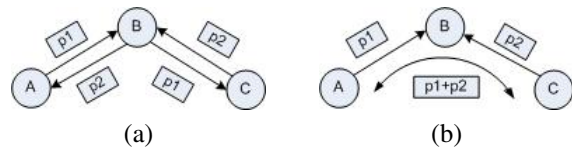


Fig. 1. (a) No-Coding (b) Network-Coding.

A. Recent work

The recent work on network coding primarily focuses on improving the network throughput [1], [2], [3] by aggressively applying coding technique described above. The work presented in [1] applies network coding to maximize network throughput at the MAC layer. Their protocol uses the known ETX [7] metric to decide the possibility of coding the packets at the relay node or central node. The authors have shown that the network coding is an excellent technique to maximize throughput. The work in [2] presented routing protocols to aggressively exploit coding opportunities in the network. The basic idea is to route the flows in the network to a region where network coding can be performed. This improves the throughput, however it greatly affects the network lifetime. Concentrating large amounts of traffic to a small region in the network burdens the involved nodes. This routing approach can eventually lead to a network breakdown. Therefore, such an approach cannot be applied to energy constrained networks.

In [3], the authors presented a coding aware routing protocol for multiple unicast sessions in a wireless mesh network. The primary objective here is to apply network coding techniques to maximize the throughput while respecting the interference

constraints due to channel capacities. They identified the trade off between routing flows for coding advantages and for avoiding interference. Although the proposed solutions are effective for energy-unaware networks, they cannot be directly applied to energy-constrained networks where network lifetime is of paramount importance.

B. This paper

The majority of earlier work on network coding addressed capacity improvement problems for multicast applications [8], [9], [10]. The specific problems they addressed are fundamentally different as they do not deal with energy or network lifetime issues.

In this paper, we apply network coding as a energy minimization technique at the routing layer and analyze the related trade offs. Applying network coding to energy limited networks requires addressing a new set of challenges and brings out the trade offs between total energy savings and network lifetime. Routing traffic to encourage network coding with the aim of minimizing the total energy consumption develops hot spots in the network. These hot spots result in poor network lifetime.

To the best of our knowledge, our work is the first to apply network coding as an energy minimization technique and study the trade off between total energy minimization and network lifetime. We analyze this trade off by addressing *Multi-Path Routing Problem* in a static manner. In future work we will present its adaption in dynamic situations.

The rest of the paper is organized as follows. In section II, we describe our system model along with a motivational example. In Section III we discuss energy aware network coding model in multi-path scenario in wireless networks. In Section IV experimental evaluation of the LP formulation proposed in the paper is discussed.

II. SYSTEM MODEL DESCRIPTION

Network topology is assumed fixed and all the nodes are monitored by a base station which computes paths based on requested connections. Base station is assumed to be a high-energy node with continuous supply of power.

Our model does not assume homogeneity with respect to energy or functionality of a node in the network. They are allowed to start with different battery powers but once deployed in the network we assume that they do not have access to the external battery devices. In the multi-path routing packets routed through different paths for the same flow might encounter variable delays and reach destination at different time. We assume destination node can take care of such unordered packets.

Network coding is discussed through a simple XOR operation on the transmitted packets. This operation requires very low energy. So we assume energy spent for XOR is negligible. A header is added to a packet to distinguish XORed packets from normal ones. The header also carries the sequence number of the packets that are XORed. This helps receiver node select relevant packet from its buffer and XOR with the

packet received to retrieve the unknown packet. To keep our model simple we consider the case where only two packets can be XORed.

A. Motivational Example

Network coding applied to energy constrained networks reduces the total energy consumed for a given amount of information across the network. Existing coding aware routing protocols discover regions in the network where there is a high probability for mixing the packet and diverts all traffic toward them. As a result, a few key nodes in the network handle high amount of traffic while others are left idle. Since residual energy depletes very fast due to network coding, key nodes die quickly compared to other nodes in the network. This leads to significant imbalance in residual energy of the nodes across the network which may result in reduced network lifetime even though a majority of the nodes are still alive and left with high residual energies.

We demonstrate the importance of designing lifetime aware routing protocols through a simple illustration. Consider the network in Fig. 2. Let there be two flows f_1 and f_2 scheduled from node S_1 to node D_1 and from node S_2 to node D_2 , respectively. Each flow has a traffic value of 100 units i.e. $t(f_1) = 100$ and $t(f_2) = 100$. Assume all the nodes have initial energy equal to 200 units. Let E_R denote the residual energy and TE denote the total energy spent by all the nodes in forwarding the given traffic. We assume a single unit of energy is consumed to forward one unit of traffic through a single link.

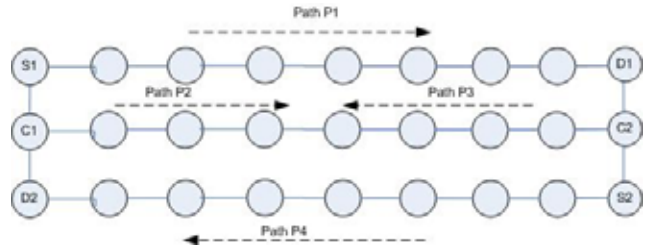


Fig. 2. An Example to illustrate the importance of lifetime aware routing

Case I : No-Coding (Shortest Path Routing)

When network coding techniques are not applied, flows f_1 and f_2 choose shortest paths P_1 and P_4 , respectively. Below we calculate the approximate total energy spent to meet the demands of two flows and residual energies in each node.

Transmissions required to forward unit traffic: 8.

$$TE = 8 * 100 + 8 * 100 = 1600 \text{ units of energy.}$$

$E_R = 200 - 100 = 100$ units. This is same for all the nodes on paths P_1 and P_4 except D_1 and D_2 .

For rest of the nodes E_R is 200 units. In this case we see that all the nodes along paths P_1 and P_4 drain to half of their initial energy, while nodes on paths P_2 and P_3 have residual energy equal to their initial value.

Case II : Coding Aware Routing

Coding aware routing protocols encourage flows f_1 and f_2 choose paths P_2 and P_3 , respectively. This is because these paths have higher path overlap. Network coding is possible when two opposite flows choose paths with same set of nodes.

Transmissions required for flow f_1 : 10.

Transmissions required for flow f_2 : 10.

Nodes where coding is possible: 7

$$TE = 10 * 100 + 10 * 100 - 7 * 100$$

In the above computation we deduct 700 units of energy because when coding is used one unit of energy is sufficient to send two packets which are XORed together.

ie., $TE = 1300$ units.

$E_R = 200 - 100 = 100$ units is same for all the nodes on paths P_2 and P_3 except corner nodes C_1 and C_2 . These nodes spend single unit of energy to transmit one unit of traffic as coding is not possible at those spots. The total traffic routed in the central route is 200 units. Corner nodes eventually die as they drain their entire energy to meet the demands of flows f_1 and f_2 .

For rest of the nodes (excluding S_1 and S_2) E_R is equal to their initial energies. The total energy spent in coding aware routing is lesser than no-coding case. But the two corner nodes are dead as they drained their entire energy. As a result network is disconnected and at this point it is dead.

Case III : Lifetime Aware Routing

Lifetime aware routing protocols encourage flows to split traffic between different paths to maximize lifetime and to minimize transmission energy. Here we assume f_1 diverts half of its traffic from path P_1 to path P_2 . Similarly, flow f_2 sends half of its traffic on the path P_3 while the other half remains on P_4 . This way traffic is balanced on all the paths and retain coding advantages.

$$TE = (TE_{no-coding} + TE_{coding}) / 2$$

ie., $TE = 1450$ units

$E_R = 200 - 50 = 150$ for all the nodes on paths P_2 and P_3 except corner nodes. While nodes on the paths P_1 and P_4 drain 50 units of energy to route 50 units of traffic.

The corner nodes in the network have dissipated 100 units of energy and still have 100 units for further communication.

Lifetime aware routing reduces total energy consumption by coding part of the traffic. Though the total energy consumed in this case is slightly higher than the case where simply coding is applied, it guarantees longer network lifetime by transmitting the traffic through all available paths.

In practice the initial and final few packets will not receive the full benefits of network coding due to timing issues, but this correction becomes insignificant for large number of packets. Therefore we neglect it in our analysis. Table I compares three routing schemes.

III. ENERGY MINIMIZATION USING NETWORK CODING

Multi-Path Routing

Our goal in this section is to impose lifetime constraints on the network and minimize total energy consumed by all the nodes in the network. The problem can be stated as follows:

	Total Energy Spent	Residual Energy Distribution	Network Lifetime
No-Coding	High	Non-Uniform	Medium
Coding Aware	Low	Non-Uniform	Low
Lifetime Aware	Medium	Uniform	High

TABLE I

GENERAL TRENDS IN THREE ROUTING STRATEGIES

Given a traffic matrix and a set of routes for each source-destination pair, our goal is to determine the amount of traffic on each path with the objective of minimizing the total energy consumed subject to lifetime constraints while making use of the network coding.

We consider multi-path routing in our model. The above problem of minimizing total energy consumption subject to lifetime constraints can be modeled as a Linear Programming (LP) problem. We use the following notations as given below.

- v : set of nodes.
- a, b, c, d, \dots : denote the node number.
- F : input set of demand
- P_i : set of paths for i^{th} demand.
- $s(i)$: source node of i^{th} demand.
- $d(i)$: source node of i^{th} demand.
- P_{ij} : j^{th} path of i^{th} demand
- f_{ij} : amount of traffic routed on path P_{ij} for i^{th} demand
- t_i : amount of traffic to be routed for the i^{th} demand.
- E_b : Energy consumption of node b in the network.
- E'_b : Initial energy of node b .
- $\gamma^{b,c}$: amount of traffic on edge bc .
- $\gamma^{a,b,c}$: amount of coded traffic onto the edges ba and bc transmitted by node b .
- CS_k denotes the clique space.

Objective function:

Minimize:

$$\sum_{\forall b \in v} E_b \quad (1)$$

where,

$$E_b = \sum_{i \in F} \sum_{j \in P_i, b \in P_{ij}, b \neq d(i)} f_{ij} - \sum_{\forall ba, bc \in e} \gamma^{a,b,c} \quad (2)$$

The objective of the linear program formulated above is to minimize sum of total energy consumed by each sensor node while routing the given traffic. Energy consumed by each node (E_b) includes the term $\sum_{i \in F} \sum_{j \in P_i, b \in P_{ij}} f_{ij}$ in Equation 2. This term corresponds to the aggregate of the flow values for all demands where node b is present in the path chosen by flow. Consider illustration shown in Fig. 3. The node 4 is in the paths P_{11} and P_{14} chosen by demand 1 and in the path P_{21} chosen by demand 2. It is involved in routing all traffic forwarded on the paths P_{11} , P_{14} and P_{21} . Node 4 can code flows on the paths P_{11} and P_{21} and broadcast on the

links $4 \rightarrow 1$ and $4 \rightarrow 6$ simultaneously. This broadcast traffic is a coded traffic and is given by term $\sum_{\forall ba, bc \in e} \gamma^{a,b,c}$ in the equation. Subtracting this term from the first term ensures that broadcast traffic is counted only once.

Flow constraint:

$$\sum_{j \in P_i} f_{ij} = t_i \quad (3)$$

The flow constraint given by Equation 3 ensures that sum of the flow values for demand i routed through multiple paths is equal to the amount of traffic to be routed for the i^{th} demand. In the illustration shown in Fig. 3, for demand 1 ($1 \rightarrow 7$) available paths are P_{11} , P_{12} , P_{13} and P_{14} . The total traffic routed through these four paths should be equal to the traffic demand from $1 \rightarrow 7$ given by t_1 . Similarly, for demand 2, traffic routed through paths P_{21} , P_{22} and P_{23} should be equal to t_2 .

Broadcast traffic constraint:

$$\gamma^{a,b,c} \leq \sum_{i \in F} \sum_{j \in P_i, ab \in P_{ij}, bc \in P_{ij}} f_{ij} \quad (4)$$

$$\gamma^{a,b,c} \leq \sum_{i \in F} \sum_{j \in P_i, cb \in P_{ij}, ba \in P_{ij}} f_{ij} \quad (5)$$

Broadcast traffic refers to the coded traffic in the present formulation. $\gamma^{a,b,c}$ is the broadcast traffic sent by node b on the links $b \rightarrow c$ and $b \rightarrow a$ after coding. Fig. 4 illustrates the broadcast traffic constraint. Node 4 receives unicast (uncoded) traffic from nodes 1, 6 and 5. Paths P_{11} , P_{21} share links $1 \leftrightarrow 4$ and $4 \leftrightarrow 6$. So, coding is possible at node 4 on the flows routed through paths P_{11} and P_{21} . The broadcast traffic on links $4 \rightarrow 1$ and $4 \rightarrow 6$ should be less than the unicast traffic sent by nodes 1 and 6 on the links $1 \rightarrow 4$ and $6 \rightarrow 4$, respectively.

The terms $\sum_{i \in F} \sum_{j \in P_i, ab \in P_{ij}, bc \in P_{ij}} f_{ij}$ in Equation 4 and $\sum_{i \in F} \sum_{j \in P_i, cb \in P_{ij}, ba \in P_{ij}} f_{ij}$ in Equation 5 correspond to the total unicast traffic forwarded on the links $a \rightarrow b$, $b \rightarrow c$ and $c \rightarrow b$, $b \rightarrow a$, respectively. The constraints in these equations ensure that node b can at most code a minimum of the unicast traffic.

Unicast traffic constraint:

$$\gamma^{b,c} = \sum_{i \in F, s(i)=b} \sum_{j \in P_i, bc \in P_{ij}} f_{ij} + \sum_{\forall a \in v} \left(\sum_{i \in F} \sum_{j \in P_i, ab \in P_{ij}, bc \in P_{ij}} f_{ij} - \gamma^{a,b,c} \right) \quad (6)$$

Unicast traffic is the uncoded traffic forwarded on a link. Traffic routed through a link can be unicast or broadcast. The unicast traffic on the link $b \rightarrow c$ is given by $\gamma^{b,c}$. In Fig. 4, link $4 \rightarrow 6$ is shared by paths P_{11} and P_{14} . Node 4 cannot code unicast traffic on path P_{14} ($5 \rightarrow 4$, $4 \rightarrow 6$) because not a single flow choose path containing links $6 \rightarrow 4$ and $4 \rightarrow 5$. Therefore the

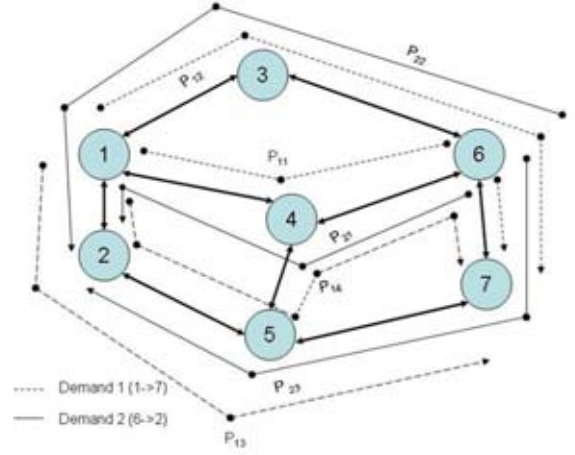


Fig. 3. Illustrates LP formulation in the network with flow demands from nodes 1 to 7 and 6 to 2

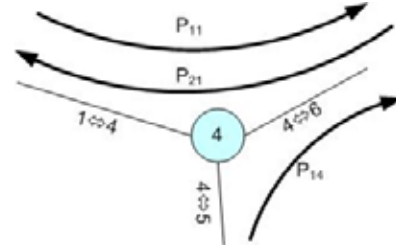


Fig. 4. A part of the network for illustrating constraints in LP formulation

traffic it receives from node 5 must be forwarded to node 6 on the link ($4 \rightarrow 6$) using unicast transmissions. The unicast traffic on this link also includes uncoded traffic at node 4 on the path P_{11} .

In Equation 6 $\sum_{\forall a \in v} (\sum_{i \in F} \sum_{j \in P_i, ab \in P_{ij}, bc \in P_{ij}} f_{ij})$ is the total traffic received by node b from its neighbor nodes and routed through the link $b \rightarrow c$. The broadcast traffic $\sum_{\forall a \in v} \gamma^{a,b,c}$ is deducted to calculate unicast traffic on the link $b \rightarrow c$. The unicast traffic $\gamma^{b,c}$ also includes flows originated at node b and forwarded on the link $b \rightarrow c$. It is given by $\sum_{i \in F, s(i)=b} \sum_{j \in P_i, bc \in P_{ij}} f_{ij}$ in the equation.

Capacity constraint:

$$\sum_{ab, xy, yz \in CS_k} \frac{\gamma^{a,b} + \gamma^{x,y,z}}{C} \leq 1, \forall CS_k \quad (7)$$

The capacity constraint ensures that at the MAC layer, all the transmissions sharing the same medium are not scheduled simultaneously. In the present example, transmissions at node 4 interrupt all the transmissions at nodes 1, 5 and 6. Node 4 shares communication medium with these nodes. All unicast and broadcast transmissions at node 4 should be carefully scheduled such that they do not effect other nodes' transmissions.

In Equation 7 the possible transmissions which share clique

with node b is given by $\sum_{ab,xy,yz \in CS_k} \gamma^{a,b} + \gamma^{x,y,z}$. This value should be less than capacity C of the link.

Lifetime constraint:

$$E'_b - E_b \geq \eta E'_b, \forall b \in v \quad (8)$$

The formulation without Equation 8 encourages network coding opportunities in the network for the given traffic load and aims at minimizing the total energy consumption. Consequently, it aggressively routes demands with the aim of maximizing energy savings. The lifetime constraint in Equation 8 ensures a minimum required network lifetime for each individual node and hence saves the network from dying. The minimum energy stored at each node is η times the initial energy after routing the given traffic.

This constraint in a way tries to achieve uniformity in residual energy distribution across the nodes in the network. A minimum residual energy requirement ensures that no single node in the network is completely run out of its battery power. In this way network can stay alive for longer duration satisfying the traffic demands.

IV. PERFORMANCE EVALUATION

A. Experimental Setup

We evaluated the proposed schemes to compare their relative performance by varying the traffic and channel capacity conditions. The formulated LP problems are evaluated using the ILOG CPLEX 10.100 software [11]. The presented scheme was evaluated on a grid topology of size $10 * 10$ with unit normalized distance between adjacent nodes. Our choice of grid topologies for the performance evaluation studies is based on the fact that they offer better network coding opportunities compared to other general topologies as a result they offer a good platform to evaluate the network coding and its trade offs. For each evaluation run, we generated 20 traffic demands with randomly chosen source and destination nodes.

We measured the normalized total energy consumption (normalized with respect to the scenario where no coding is performed and each demand is routed via the shortest path) and the average standard deviation to compare the relative performance of the following two schemes: Energy minimization using network coding (EM-LP) and energy minimization with a lifetime constraint (LTC-LP). The first scheme had no lifetime constraint while the second scheme did consider a lifetime constraint.

The following parameters were varied in our evaluation studies:

- Channel capacity factor: ratio of channel capacity to the total demand traffic in the network;
- Traffic load factor: ratio of total demand traffic to the channel capacity; the amount of traffic is kept fixed while varying the channel capacity factor and while the channel capacity is fixed when varying the traffic factor;
- Lifetime constraint (η).

B. Results

Effect of channel capacity on energy consumption:

Fig. 5a compares the relative performance of LTC-LP-10 (LTC-LP with $\eta = 0.10$) and LTC-LP-5 (LTC-LP with $\eta = 0.05$) with the EM-LP. As channel capacity is increased for a given traffic load, more traffic can be sent via the same path while still respecting the MAC constraints. In other words, with the increasing channel capacity factor the opportunity for network coding increases as a result, and the normalized energy consumption for all schemes decreases in the figure. However, as we further increase the channel capacity for LTC-LP we hit a point where we do not show further energy reductions. This is because of the lifetime constraints imposed on the individual nodes, which constrain the amount of traffic routed via each path in the network. This trend is particularly seen in LTC-LP-10 where the lifetime constraints on the individual nodes are higher. The EM-LP curve also stabilizes after exploiting all network coding opportunities as shown in the figure. EM-LP shows more than 30% improvement over the non-coding based routing, the LTC-LP-10 shows about 27% improvement over the non-coding based routing.

Effect of traffic factor on energy consumption:

Fig. 5b compares the relative performance of LTC-LP (with $\eta = 0.20$) and EM-LP schemes by varying the traffic factor. As the traffic load is increased for a given channel capacity, the network coding opportunity initially increases as more traffic is available to perform better traffic mixing. However, as the traffic is further increased the energy reductions due to network coding are surpassed by the increase in energy consumption from the increased workload. Consequently, both schemes show an increased normalized energy consumption after the traffic factor of 0.6. In this figure, the LTC-LP and EM-LP schemes show an improvement of 28% and 35% over the non-coding based routing at traffic factor 0.9 .

Effect of traffic factor on residual energy distribution:

Fig. 5c depicts the effect of traffic factor on the standard deviation of the remaining energy values of the individual nodes in the network. The standard deviation values are normalized with a suitable and large enough number. In the figure, the EM-LP shows a huge standard deviation implying that the residual energies among the individual nodes after handling the given traffic are very unevenly distributed. As the traffic increases, the traffic is more widely spread and hence the standard deviation decreases for both the schemes as shown in the figure. Throughout, the LTC-LP ($\eta = 0.20$) scheme which tries to spread the traffic across the network to meet the lifetime constraints achieves better residual energy distribution.

Effect of channel capacity factor on residual energy distribution:

Fig. 5c compares the residual energy distributions of LTC-LP (with $\eta = 0.20$) and EM-LP schemes by varying the

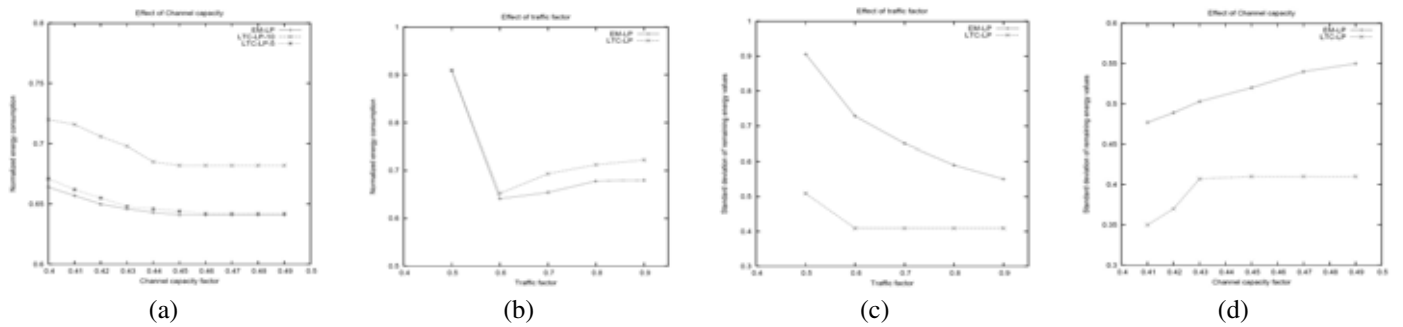


Fig. 5. (a) Channel capacity v/s Energy consumption (b) Traffic factor v/s Energy consumption (c) Traffic factor v/s Residual energy distribution (d) Channel Capacity v/s Residual energy distribution

channel capacity for a given traffic. As the channel capacity is increased the opportunity for network coding increases as a result there is more room for the traffic to be routed via a single path and achieve higher coding gains. However, this results in more skewed traffic distribution and higher standard deviation values. However, as we further increase the traffic the LTC-LP scheme stabilizes due to energy constraints and limits the traffic load distribution from further skewing. Throughout, the LTC-LP ($\eta = 0.20$) shows better standard deviation values than the EM-LP scheme.

V. CONCLUSION

Energy management is the key issue in the design and operation of various battery driven embedded devices. In this paper we showed that network coding, a technique originally introduced to maximize throughput, can be used as a technique to save energy by minimizing the number of transmissions needed in a wireless network to deliver a packet. We explored the trade off between selecting paths where network coding can be used and network lifetime, which is adversely effected when aggressive use of this technique creates hot spots where nodes die quickly disconnecting the network.

This exploration was done by comparing the transmission energy use by shortest path routing with the results of LP one of which aggressively used the technique (EM-LP), the other guaranteed network lifetime by ensuring all nodes retained a specified fraction of their energy (LTC-LP). Both saved energy when compared to shortest path routing. The saving provided when network lifetime is guaranteed is slightly less and residual energy more evenly distributed, since traffic is distributed amongst more paths.

The main contribution of this work is it shows network coding aware routing saves energy. However for a number of wireless networks, the traffic demands may change before the base station can solve the ILP or other practical issues may prevent the direct application of this scheme.

This approach can be used as a benchmark to evaluate the performance of a more practical heuristics. Developing a practical distributed heuristic is a work in progress.

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