A Study of Joint Network Coding and Power Control in Energy Harvesting Networks

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A Study of Joint Network Coding and Power Control in Energy Harvesting Networks

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Faculty of Electrical Engineering, Mathematics and Computer Science Delft University of Technology Delft, The Netherlands
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by

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in partial fulfillment of the requirements for the degree of

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Dr. Ir. F. A. Kuipers
Abstract

Wireless sensor network comprising of energy harvesting (EH) devices is a system that derives energy from the environment. The energy from external source is not continuous and the amount of energy harvested in the network is highly variable. Therefore the challenge in such networks is to efficiently utilize the varying energy within the node and across the network and yet meet performance objectives. In this thesis we consider the possibility of network coding along with adaptive power control for data transmission in linear EH networks and study techniques to maximize throughput and to manage energy consumption in the system. Traditional power control techniques aim to mitigate multiple user interference or increase signal to noise ratio in the network. On the other hand, the power control technique used here is to increase transmission range to sustain communication and create network coding opportunities at the intermediate nodes. This in turn minimizes the number of transmissions and receptions required to exchange information across the network resulting in a net increase in throughput. Our results show that the network coding along with power control technique gives higher data throughput along with reduction in total energy consumption of the network when compared to either network coding or simple data forwarding.
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Applications using wireless sensor network (WSN) are becoming common nowadays and are set to increase. The WSNs have a huge potential across numerous remote monitoring and control applications like battlefield surveillance, health care, asset management, smart homes, environment monitoring and forecasting. The sensor nodes used in these applications are usually battery operated and this limits the operational time of the sensor devices. On the other hand, there is a need in a majority of WSN applications for these nodes to be in perpetual operation. Hence the key challenge in such networks is to minimize the energy usage in order to extend the sensor network’s operational lifetime. This problem has been partially addressed by several low power consumption techniques, viz. energy efficient scheduling, routing and adaptive power control. However, when a sensor is depleted of energy, it is no longer useful and cannot contribute to the utility of the network unless the energy is replenished by means of recharging or replacing the batteries. This is an other problem in battery operated sensor network. The replacement of batteries becomes a bottleneck for applications involving a large number of sensors (eg: sensing soil moisture in agricultural field) or sensors deployed in places that are hard to reach (eg: structural health monitoring of critical infrastructures or buildings). In order to overcome these limitations, the sensor nodes are expected to be equipped with energy harvesting mechanisms and hence eliminate the need to replace batteries and have an extremely long lifetime.

In the reminder of the chapter we introduce energy harvesting networks along with its energy characteristics. Following this, a short overview of current literature is presented. Particular attention is paid to energy management techniques in these networks. In the last part of this chapter, the problem statement is made and the thesis organization is presented.
1-1 Energy Harvesting networks

Energy harvesting (EH) is the process of deriving energy from the external source. Some of these are solar, thermal, wind, vibrational and RF energy sources. The devices equipped with EH mechanism convert energy from one or more of the above sources to consumable electrical energy, store it in a battery and utilize it for any desired operation.

The EH devices are capable of recharging themselves and this eliminates the need to replace batteries. The desk calculator powered using solar cell is an example of EH device. Unlike battery operated devices, the energy from EH source is unlimited which in turn leads to almost infinite lifetime of EH devices. That is, even when the energy in EH device is exhausted, it may start operating again at the next energy harvesting opportunity.

The nature of EH sources can be classified as uncontrolled but predictable, uncontrollable and unpredictable, fully controllable and partially controllable [1]. For instance, solar energy can be harvested only in the presence of sunlight, energy from a kinetic source can be extracted only when motion is present and therefore the energy harvesting cannot happen at all times. This shows that the energy from an EH source may not be available continuously. Further, the amount of energy harvested by an EH node depends on the efficiency of harvesting source. This in turn results in the residual energy within an EH node to be highly variable and this is a key difference compared to the battery operated devices. In the latter the residual energy stored in the battery decreases monotonically over time while the former case shows a random nature. This is depicted in Figure 1-1.

Moreover, the energy harvesting opportunity for the nodes may not be identical all over the network. For instance, EH sensors based on solar energy have better harvesting opportunity when exposed to direct sunlight, than those in a shadowed area. Therefore the energy harvested by EH nodes may vary across the network.

Figure 1-1: Residual energy in battery operated device and in an EH device
This is shown in Figure 1-2 illustrating a network of four nodes with the residual energy highlighted in green.

![Network Diagram](image)

**Figure 1-2: Battery-powered WSN Vs EH WSN**

In battery operated WSN, the residual energy in the nodes is more or less of a constant level as shown in Figure 1-2(a), while in EH WSN, each node in the network has different amount of residual energy as shown in Figure 1-2(b).

From the above, it is clear that the varying nature of energy within the EH node and across the network is the unique feature of EH network. The challenge in such networks is to utilize this varying harvested energy efficiently and yet meet performance objectives like desired throughput, less transmission delay, etc.

### 1-2 Literature Survey

Energy harvesting mechanism is most suitable for devices that demand small amounts of continuous power for their operation. Wireless sensor nodes in general, are devices which need to consume low power over a long time. Hence EH technology in wireless sensors has received significant attention because of the possibility of perpetual operation of the node and therefore sustain the network of sensors for a much longer time [2]. An innovative system design for EH sensors with extreme low power operation capability is demonstrated in [3]. In [4], [2], various energy harvesting techniques that are applicable to WSN applications are discussed. Some of these are wireless sensors harvesting energy from the solar source to monitor civil infrastructure [5] and wireless sensors harvesting energy from the vibrations (kinetic energy) caused by vehicles that pass over the sensors to monitor traffic [6].

In addition to harvesting energy, managing the varying harvested energy is crucial in EH networks both at node and network level. The goal of energy management techniques is to adapt to the random nature of the energy available from the environment and maximize the utility of the application. For instance, when the available energy is less for certain duration or when the energy is harvested at a low rate, energy management techniques that conserve energy yet meet the performance are required [7]. However, when there is an abundance of energy (eg. solar cell exposed to bright sunlight), then techniques that utilizes the energy and maximize performance (eg. throughput) is required. These are two conflicting requirements, where
one needs to conserve energy at a certain time, and disregard energy consumption at all other times. Therefore energy management is important in EH networks. In the following we present some of the energy management techniques proposed in the previous literature.

1-2-1 Energy Neutrality

The rate at which harvested energy has to be utilized is governed by energy neutrality. This is essential for sustained and perpetual operation of an EH sensor node. This is also the condition that is required in most energy management techniques. Energy neutrality is attained when the energy consumed by an EH node equals the energy harvested by the node in a given time. This can be further expressed as follows. If $P_h(t)$ is the harvesting transducer’s power output at time $t$, then the power $P_c(t)$ consumed by the EH sensor must $\leq P_h(t)$. When an EH node satisfies this condition, it is said to operate in energy neutral mode. This makes sustained operation of the EH node possible [1], [8]. Again, following [1], the condition for energy neutrality can be written as,

$$\eta \int_0^T [P_h(t) - P_c(t)]^+ \, dt - \int_0^T [P_c(t) - P_h(t)]^+ \, dt - \int_0^T P_{\text{leak}} \, dt + B_0 \geq 0 \forall T \in [0, \infty]$$  (1-1)

where $\eta$ is the battery storage efficiency and $\eta \in (0,1)$, $P_{\text{leak}}$, the constant that quantifies power leakage from the battery, $B_0$ is the energy stored in the battery at time $t = 0$ and the function $[x]^+ = x$ if $x > 0$ and is zero otherwise.

1-2-2 Energy Management Techniques

In EH networks, energy consumed by a node needs to be managed in order to meet the energy neutrality criterion and thereby allow infinite network lifetime. A few energy management techniques discussed in previous work include adaptive power control [7] [9], adaptive duty cycling [10], [11], harvesting environment aware routing [8], harvested energy aware routing [12] and cross layer optimization [13]. These are further elaborated below.

a. Adaptive power control - In [7], energy management is done by means of adaptive power control using a truncated channel inversion (TCI) scheme. In TCI power control method, data transmission is suspended when the instantaneous channel power falls below a certain threshold (as in during deep fades of the received signal, which are caused by multipath propagation) and the transmit power is made proportional to the inverse of the power in the faded channel. In this technique, the channel is probed periodically and the instantaneous channel state is sensed. The data is then sent at a suitable transmit power that ensures reliable communication. The chosen transmit power in turn depends on the measured power in the reception channel. When this channel is
less noisy, a lower transmit power is chosen and vice versa. However, if the energy harvested in the given time slot does not support the chosen transmit power, then the transmission is suspended (thus satisfying energy neutrality) and the harvested energy is stored in a battery which is used for future data transmission. Over a long time, a better data throughput is achieved because of energy conservation during suspended transmission and bursty transmission when adequate power is available.

b. Adaptive duty cycling - In this technique, the operational time of the EH device is varied based on its harvested energy. Algorithms which obey energy neutrality and manage energy by dynamically varying the duty cycle of the EH node are discussed in [10] and [11]. In one of these algorithms, future energy harvesting opportunities are predicted based on historical data and a suitable duty cycle is set [10]. The variance that often occurs between the predicted and actual energy harvested is dealt in [11].

c. Harvested energy aware routing - In this technique, the routing of data is based on the harvested energy. As discussed in [12], this is done in order to maximize throughput and to distribute workload evenly across the network. The author also defines the condition of energetically sustainable which is achieved when the harvested energy is greater than the power required to process and transmit/receive data. This in turn satisfies the energy neutral operation. The workload, maximum energetically sustainable workload (MESW) is then distributed across the network while satisfying the condition above. MESW is computed by accounting for the maximal environmental power and by estimating the harvested energy at each node in the network. In addition to the above, the author presents an optimal routing algorithm which sustains MESW. The simulation results presented in [12] show that the routing algorithms which do not take environmental power distribution into account lead to unsustainable operation.

d. Harvesting environment aware routing - In this technique, the energy consumed in the network is managed by means choosing the routes that are based on the harvesting environment [8]. Unlike the above mentioned techniques which consider the instantaneous available harvested energy, the algorithm proposed in [8] considers the harvesting environment. In other words, the nodes in the best route are chosen based on the harvesting opportunity of the node and not on the energy harvested in the node. For example, if node A in the network is located in shade and node B is illuminated by bright sunlight, then the node B is chosen in the route because of its better harvesting opportunity. Even under certain circumstances if node A has more energy harvested compared to node B, the routing algorithm chooses node B and not node A. Therefore the cost metric of the best path is determined by the environment of the node and its energy harvesting potential is expressed as follows:

\[ E_i = w \rho_i + (1 - w) B_i \]  

where \( E_i \) is the energy potential of node \( i \) harvesting energy at rate \( \rho_i \). \( B_i \) is the...
residual energy that is stored in the battery and the weight parameter $0 \leq w \leq 1$. The weight $w$ is closer to 1 for nodes with better harvesting opportunity.

In this manner, the cost metric is determined by the harvesting environment in [8] and by the harvested energy in [12]. Both these methods aim to distribute workload and attain sustained operation of the network.

e. Cross layer optimization – In [13], a technique that does joint power control, scheduling and routing optimization in EH networks is studied. The authors further suggest several computationally efficient sub-optimal algorithms. The data packets in this case are routed by using the network coding technique which exploits the broadcasting property of wireless networks and results in improved system performance. In [14], a networking protocol from a cross-layer perspective that combines various energy management techniques mentioned above along with network coding technique is presented. In [15], a framework that integrates energy harvesting aware routing, adaptive duty cycling along with network coding is presented. The experimental results shows energy conservation through opportunistic network coding.

From the above, it is evident that energy management is a very basic requirement of EH networks. In particular, the network coding technique mentioned above, has the potential to improve system throughput while reducing energy consumption and this is discussed below.

## 1-3 Network Coding

Network coding [16] is an emerging technique that provides significant improvements over classical routing algorithms and have interesting applications in practical networks [17]. Unlike traditional routing schemes that treat data streams like water flowing through pipes, cars in the road, etc., by keeping the independent data streams separate and only forwarding data, the network coding technique processes the data by combining the data streams and then forwarding the data.

In the case of wireless applications, the broadcast and superposition properties of the wireless channel can be readily exploited for combining data which is the basic network coding operation. The technique is explained in detail in Chapter 2. Some possible benefits attained through network coding are increased throughput, energy efficiency, robustness, security and/or reduced latency. In WSNs, the network coding has received significant interest primarily due to the energy benefits [18], [19], [20]. Several studies address the possible bounds on the throughput in different network topologies using multicast or unicast message transmission methods [21], [22].

Additionally, the energy benefits of network coding when combined with power control has been explored in [23] and in [24]. In [23], the author shows that the increase in transmission range enables more coding opportunities in a rectangular grid network and improves the overall throughput in the network. Similarly, energy
and bandwidth efficiency are achieved by means of network coding and power control in battery operated wireless linear network [24]. In this thesis, we consider this idea of network coding along with power control for EH networks.

### 1-4 Problem Definition

In this section, we state the research question that forms the subject of this thesis. From the above discussion, it is evident that energy management is a prime objective in sensor networks. The control of the radio transmit power is one way to manage energy consumption. In the rest of this thesis, we use power control and energy management interchangeably. The need for power control is now examined, and we consider battery operated WSNs for the purpose. In battery operated WSN, energy conservation in sensor nodes is essential to increase the lifetime of the node. This in turn extends the operating lifetime of the network. In order to conserve energy in the node, the sensor nodes are designed to operate at fixed and optimal transmit power. If higher transmit powers are used then the energy in the battery deplete faster and the node eventually shuts down. If considerable amount of nodes in the network shuts down, the network may not be connected and the network will be no longer operational. However, the idea of power control is not completely eliminated in battery operated WSNs. The increase in transmit power is required to achieve system performance. For instance, in some network topologies, increase in transmit power is required in order to reduce packet error probability in the network, to vary the transmission range and to balance load across the nodes in the network [25].

Contrary to the battery-operated WSNs, energy conservation in EH nodes is essential only when the rate at which the energy harvested is low. However, when the node has a good energy harvesting opportunity, it can afford to increase its transmit power and use power control to achieve a higher signal to noise ratio, or improve connectivity in the network.

This is further illustrated as follows. Consider a solar based EH WSN which is well-illuminated by sunlight. In this case, the nodes harvest energy at a higher rate. If this energy is not consumed at the same rate, then the incoming energy may go wasted beyond few minutes as the storage devices become full. Therefore, the excess harvested energy can be used to increase transmit power which in turn improves system throughput and hence performance. Similarly, the same network may harvest energy at a very low rate (for instance when some nodes are in the shadow) or may not harvest any energy at all for certain duration (during the absence of sunlight). In this case, the nodes have to efficiently utilize the available harvested energy and the energy conservation techniques become essential. Therefore, the network coding technique which can conserve energy and also improve throughput is highly suitable for such applications.

The idea of joint network coding and power control has been considered in previous work [24], [23] for battery operated wireless network. However, in this thesis we examine the possibility of network coding along with adaptive power control in order to handle the varying nature of energy in EH networks. We further find the
performance benefits that this combination can offer in EH networks. Moreover, to evaluate the performance of joint network coding and power control technique, we compare the results with existing data transmission techniques - the plain network coding and simple data forwarding. A somewhat similar approach can be found in [24], where the energy efficiency is computed based only on the transmit power, while in this work we also consider energy consumption due to reception and system energy associated to data transmission on energy conservation.

1-5 Organization of the thesis

In Chapter 2, we develop the system model which describes the network, data traffic and scheduling policy. The different data transmission algorithms simple Data Forwarding (DF), Network Coding (NC), joint Network Coding and Power Control (NCPC) that are studied in this thesis are introduced.

In Chapter 3, we study the performance improvements of NCPC over other two techniques in a network of nodes with moderate energy availability. We describe an algorithm used to evaluate the throughput and energy consumption in the three different data transmission techniques. The algorithm is implemented in C from which various performance metrics are computed.

In Chapter 4, we study the performance of NCPC technique for various energy situations in an EH network over simple DF technique. We also present a power control algorithm that adapts to this varying energy situation and improve the system performance. The benefits in terms of throughput and energy consumption of joint network coding and power control in EH networks are illustrated.

The Chapter 5 we conclude our study on the performance of joint network coding and power control technique over EH networks and suggest some directions for future work.
In this chapter, we begin by introducing a minimal system. We will limit the
discussion to the network and traffic aspects of this system, as these are used for
later analysis. In this network three different data transmission algorithms are
studied and they are simple data forwarding (DF), network coding (NC), and joint
network coding and power control (NCPC). These algorithms are analyzed in order
to estimate the energy and throughput benefits of the joint network coding and
power control technique over the other two. Also details on the media access control
(MAC), scheduling and the energy model are described. The energy model is used
to compute the total energy consumed by the network.

2-1 Network and traffic model

We consider a simple and fundamental network topology - the line network in
which the nodes are placed in tandem and equidistant to each other. Nodes in
the network communicate by means of unicasting, multicasting or broadcasting
data packets. Multicast and multiple unicast are commonly used in analyzing the
network coding technique [23]. For the line network, we consider a multiple unicast
traffic. Unicast traffic is when a single sender transmits data to a single receiver
through the network. Information exchange between two nodes can be seen as
two unicast sessions. We consider a scenario in which the end nodes of the line
network generate information and exchange them via the intermediate nodes. The
information is divided into packets of equal size each. Let N be the total number of
nodes in the network. Let the packet stream be represented as $x_1, x_2, x_3$, which is
generated by the node at the left end (the node 1) and is called right bound packets.
Similarly, the stream $y_1, y_2, y_3$... from the node on the right end (the node N)
is called left bound packets. The intermediate nodes act only as relays and do not
generate any packets.
2-2 Data transmission techniques

The three data transmission techniques used in the network above are explained in this section. In multihop communication, an intermediate node relays the data packet to another. Relaying may just be packet forwarding or may be forwarded after the packets are combined by network coding. In addition, the transmit power may be controlled, in order to increase or decrease the transmission range. The above can then result in the classification shown in Table 2-1.

<table>
<thead>
<tr>
<th>Set</th>
<th>Network Coding</th>
<th>Power Control</th>
<th>Technique</th>
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<tbody>
<tr>
<td>A</td>
<td>No</td>
<td>No</td>
<td>simple Data Forwarding</td>
</tr>
<tr>
<td>B</td>
<td>No</td>
<td>Yes</td>
<td>joint Data Forwarding and Power Control</td>
</tr>
<tr>
<td>C</td>
<td>Yes</td>
<td>No</td>
<td>Network Coding</td>
</tr>
<tr>
<td>D</td>
<td>Yes</td>
<td>Yes</td>
<td>joint Network Coding and Power Control</td>
</tr>
</tbody>
</table>

Table 2-1: Possible combinations in relaying of data.

Each technique mentioned in Table 2-1 can be implemented by a collection of algorithms belong to the sets A, B, C or D. An optimal algorithm in each set can be determined based on the application, network topology or performance objectives. From these sets, we choose three algorithms, viz. DF, NC and NCPC from sets A, C and D respectively, for the analysis in the rest of this work. These algorithms are relevant to the network and traffic model considered above.

We do not consider joint data forwarding and power control due the following reason (set B in the table above). The two main operations in the network that influences overall energy consumption and throughput in the network are transmissions and receptions. Hence energy conservation or increase in throughput is achieved through reducing total number of transmissions and/or receptions in the network. In [17], [18], it is shown that the network coding is an improvement in terms total throughput and energy consumption over the simple data forwarding technique. This is because it reduces the total number of transmissions. Therefore we consider the effect of power control only in network coding instead of simple data forwarding.

The different data transmission algorithms that will be analyzed are explained using an illustration. Consider a line network of five nodes placed at equal distance. The end nodes 1 and 5 exchange data packets $x$ and $y$ via the intermediate nodes 2, 3 and 4.

In DF, an intermediate node forwards the data packet to the next hop neighbour node. An intermediate node $n$ transmits either right bound packet to right neighbour node $n + 1$ or the left bound packet to left neighbour node $n − 1$. This is further depicted in Figure 2-1.
In NC, the network coding operation is performed by several intermediate nodes and over the packets from different unicast sessions. Whenever an intermediate node has both right bound packet and left bound packet to transmit, the packets are combined through an XOR operation. This network coded packet is then broadcasted to the neighbour nodes located at one hop distance. This is illustrated in Figure 2-2 where the intermediate node 3 performs $x \oplus y$ and broadcasts the network coded packet to nodes 2 and 4. It is clear that this operation minimizes total number of transmissions by that node and therefore energy is conserved. Further, when several nodes in the network perform network coding operation the overall number of transmissions reduce which result in an increase in throughput and a decrease in the total energy consumed across the network. It is therefore evident, that network coding is a big improvement over DF. When the end nodes receive
the network coded packet, it further performs a XOR operation to retrieve its own packet. In this example, the node 1 performs \(x \oplus y \oplus x\) to retrieve \(y\) and node 5 performs \(x \oplus y \oplus y\) to retrieve \(x\).

In NCPC technique, the transmission range is increased to two hop distance by transmit power control only in the nodes that perform network coding. Note that this implies that the transmit power needs to be increased by a factor of 4 when the transmission range is doubled (this is further discussed in Chapter 3). Our motivation in choosing two hop-distance comes from the specifications of practical hardware. Referring to a typical radio transceiver chip (CC2420 [26]), it is seen that the typical operating region for this chip is between -25 dBm to 0 dBm. Conservatively, we choose a level of -10 dBm which is in the middle of this range. This allows a maximum power control of a factor of 10, which in turn allows a transmission range increase of \(\sqrt{10}\). We choose a hop distance of two to be on the conservative side, as this may include the sensor devices operating in extreme environments that have higher losses.

The choice of controlling power only in nodes that participate in network coding is for the following reason. As seen in the previous section, the very operation of network coding results in higher throughput and reduced energy consumption when compared to the DF technique. This is again due to the reduced number of transmissions. Increasing transmit power in these nodes will therefore result in a further reduction of transmissions. This implies that the neighbour nodes at one hop distance do not receive the data packet. Stated otherwise, the total number of transmissions and receptions reduce by a factor of 2 compared to power control by the nodes that forwards packet without network coding. This is shown in Figure 2-3, in which node 3 performs network coding and then transmits the data packets to nodes 1 and 5. The nodes within the transmission range, 2 and 4 do not receive data packets and hence the total number of transmissions and receptions are further reduced compared to NC technique.

\section{2-3 Node model}

For data transmission using the algorithms explained above, a suitable model for node is developed here. We assume time slots of fixed duration \(t\). In a given slot, the nodes in the line network can be in either \textit{sleep} or \textit{wake} mode. When in wake mode, a node can either transmit or receive single data packet. The node remains in sleep state otherwise.

It is possible that the intermediate nodes will have to store the packet if it cannot access the channel in the given time slot. Hence we assume that the intermediate nodes transmit data by means of \textit{store and forward} mechanism. For this operation, we assume left and right buffers of infinite depth to store \textit{left} and \textit{right} bound packets respectively before forwarding to the neighbour node. For this reason, the nodes need to be equipped with an omni-directional radio module. This is depicted in Figure 2-4.
In a given time slot, the nodes that have data to transmit contend to access the common channel. We assume that this contention is resolved using the IEEE 802.11 CSMA/CA based MAC in which the channel is accessed through Ready to Send/Clear to Send (RTS/CTS) mechanisms. In Carrier Sensing Multiple Access/Collision Avoidance (CSMA/CA) technique, the node that has data to transmit senses the channel before transmitting data. If the channel is free, then the node sends a RTS frame to the destination node. The destination node then replies with a CTS frame after which the actual data packet is transmitted. The RTS/CTS frames are always broadcasted. Therefore, any other node that receives a RTS or CTS frame refrains from data transmission to these nodes for a certain duration specified in the RTS/CTS frames. This way the collisions at the time of data transmissions are avoided. If channel is found to be busy, then the node defers its transmission for a random amount of time.

2-4 Scheduling

In wireless networks with several unicast sessions in progress, MAC scheduling is required to allocate the channel to these sessions. Furthermore, performance objectives like throughput and energy efficiency have to be met by the network. Therefore, designing an appropriate scheduling scheme is essential and more critical in network coding technique. If not, this may lead to poorer performance compared to traditional routing technique [27]. In many scheduling algorithms, the optimization of these performance measures cannot be characterized by a single criterion. For instance, in [28], the authors show that the throughput of the system depends on the network topology, the generation size and the field size. Moreover, a scheduling algorithm optimal for one performance metric may not be optimal for another. For instance, a throughput optimization algorithm may involve a trade off between the transmission and processing energy costs and may not be energy efficient [29], [30].

In this thesis, we construct a scheduling algorithm based on the strategies proposed in the literature mentioned above and optimal for both throughput and energy consumption. The scheduling decision for a given time slot determines the sessions that are to be handled and corresponding channel (also known as link) that need to be activated. This is done as follows:
• The sessions that are to be handled in a given timeslot is determined by the sequence number of the packet in head of line (HoL) of the right/left buffers. The nodes with lowest sequence number have an higher priority and so transmit data in that timeslot.

• The channels associated with these nodes are then activated.

### 2-5 Energy consumption model

Several operations in the nodes contribute to the total energy costs of the network. Operations in the intermediate nodes, in order to relay data packets are data transmission, reception and data processing (in the case of network coding technique). The total energy consumed for transmitting and receiving a single data packet can be written as follows.

\[ E = E_t + E_r + E_p \]  \hspace{1cm} (2-1)

where \( E_t \) is the energy required to transmit data packet at certain transmit power, \( E_r \) the energy required to receive a data packet and \( E_p \) is the energy consumed for processing (network coding operation) the data packets. The transmission energy \( E_t \) can be further divided into two components – \( E_{tp} \), the energy consumed for data transmission alone at certain transmit power \( P_t \) and for certain duration \( t \), and \( E_c \) the associated hardware cost which is the energy consumed by transmission supporting circuits. This can be expressed as follows.

\[ E_t = E_{tp} + E_c \]  \hspace{1cm} (2-2)

\( E_{tp} \) can be further written as

\[ E_{tp} = P_t \ast t \]  \hspace{1cm} (2-3)

Since the data packet are of fixed size, transmission energy \( E_t \) varies only for different transmit powers \( P_t \) as per the above equation. The reception energy \( E_r \) which is also the sum of energy required for packet reception and its supporting hardware cost is a fixed value. This is because the data packets are usually received at a fixed power and for a given size of data packet, the reception energy \( E_r \) is a constant.
Chapter 3

Data Transmission Algorithms for Information Exchange

In the previous chapter, three data transmission algorithms were introduced. We begin by studying the performance of the Network Coding and Power Control (NCPC) algorithm in an environment in which the nodes harvest energy at low rate or have limited energy. For instance, in a solar energy based EH-WSN, the nodes may not harvest energy during night time in the absence of sunlight.

The performance metrics we use are the throughput and total energy consumption. These are quantified by means of the total number of time slots, transmissions and receptions required to complete exchange of messages. In order to determine these values for different number of nodes and messages exchanged, we implemented the three data transmission algorithms viz. DF, NC and NCPC using the C programming language. We also describe the scheduling strategy used in these algorithms and discuss the throughput and associated energy cost (total energy consumption in the network) results obtained.

3-1 Implementation of the algorithms

Here we explain the C programming logic with an emphasis on the scheduling strategy. We outline an algorithm that consist of three phases – initialization, scheduling, data transmission and buffer update in order to exchange message between the end nodes of a line network. Only the scheduling step varies for the different data transmission algorithms. At the end of the initialization step, the data packets are made available at the end nodes. At the beginning of every time slot, the scheduling decisions are made followed by channel activation. This is accomplished in the scheduling step (as explained in [29]). Following this the data transmission and buffer update procedure is done. The complete operation is represented using a flowchart in Figure 3-1.
Data Transmission Algorithms for Information Exchange

START

INITIALIZATION
Initialize right and left queues of 1st and nth nodes with x and y sequence respectively

IF
left queue of 1st node has all y sequence
AND
right queue of nth node has all x sequence

YES

Scheduling

STOP

Data transmission and buffer update

Figure 3-1: A flowchart for the message exchange in a line network
The implementation details of the three different phases in data transmission are illustrated as follows. Consider a line network comprising of 9 nodes in which the end nodes (1 and 9) exchange three packets each ($x_1$, $x_2$, $x_3$ and $y_1$, $y_2$, $y_3$) via intermediate nodes 2 to 8.

**Step 1 - Initialization**

In this phase, the data packets that are to be transmitted are initialized at the end nodes. The *right bound packets* and *left bound packets* are stored in the right and left buffers of nodes 1 and 9 respectively. Figure 3-2 shows the status of nodes after initialization. The buffers in the end nodes have data packets while the intermediate nodes have their buffers empty.

![Figure 3-2: Status of the buffers and the packet position after initialization](image)

**Step 2 - Scheduling**

In a wireless network comprising of multiple data transmission sessions, scheduling is required to determine *conflict free* active links or channels in the network [29]. The channels are said to be conflict free when a channel is allocated to a unique source-destination node pair. In the scheduling step, the packets that should be transmitted are determined and the corresponding channels are activated. This step is executed at the beginning of every time slot. In this work, conflict free scheduling is based on the sequence number of the packet and the implementation in C is as follows.

In each node, the packets at the head of line (HoL) of the left and right buffers are compared and the smaller of these two sequence numbers is determined. Following this stage, the lowest of the sequence numbers from the preceding step is determined across the whole network. The nodes that have data packet with the lowest sequence number are given a higher priority and the links corresponding to these nodes are activated. Following this, the nodes with next lowest sequence number are given priority. If the links corresponding to the second lowest sequence number are conflict free, then the links are activated. This procedure is repeated for all nodes in the entire network. This is further represented using a flow chart in Figure 3-3.

**Step 3 - Data transmission and buffer update**

Once scheduling decisions are made, the data is transmitted. This is implemented by updating the buffers of the nodes that transmit and receive data packets. The
Data Transmission Algorithms for Information Exchange

Figure 3-3: Flowchart representing scheduling operation in a line network and for a given time slot
following are the possible scenarios for data transmission and reception at the intermediate nodes.

1. If the left buffer of an intermediate node $n$ is empty and has data packet only in its right buffer, then the packet is transmitted to the right buffer of node $n + 1$. This is done by updating this node with the sequence number of the new right bound packet.

2. If the right buffer of an intermediate node $n$ is empty and the left queue non-empty, then this data is transmitted to the left buffer of node $n - 1$. In the algorithm, this is done by updating the node with the sequence number of the new left bound packet.

3. If an intermediate $n$ node has both right and left buffers non-empty, then in case of DF, only the right bound data packet transmission is handled in that time slot. The left bound data packet is transmitted in the next timeslot. In the case of NC algorithm, both packets are handled in the same time slot. i.e the packets are network coded and transmitted to both right and left neighbours simultaneously. The network coded packet is transmitted to left and right buffers of nodes $n - 1$ and $n + 1$ respectively. The network coding operation is similar in NCPC algorithm with the addition of power control. In NCPC algorithm, the nodes that perform network coding also increase the transmission range to two hop distance. Therefore the network coded packet is transmitted to left and right buffers of nodes $n - 2$ and $n + 2$ respectively. In this case the nodes at one hop distance $n - 1$ and $n + 1$ which is in between the source and destination intermediate nodes do not receive any data packet and remains in sleep mode.

After data transmission, the data packet is removed from buffer of the intermediate node $n$. On data reception, the buffers are updated with the new packets and are further sorted in such a way that the packet with lowest sequence number is placed at the HoL of the buffer. The sorting operation is to show a priority queue in which the packets with lowest sequence number gets higher priority.

The data transmission in conflict free channels for different algorithms are illustrated as follows. At a given time slot, assume that the buffers are populated with the data packets as shown in Figure 3-4. The packets with lowest sequence numbers $x_1$ and $y_1$ are in node 5. Following this, a conflict-free transmission channel is chosen to send the packet.

In DF algorithm, a channel is acquired for transmitting $x_1$ from node 5 to 6. The state of node 4 is also set to be busy as the packet from node 5 is transmitted using an omni-directional antenna. The busy state also resolves one more issue: when node 4 is in reception mode, then transmission from node 5 to 6 can cause interference. This is also the reason for packet $x_2$ not being sent from node 3 to 4. On the other hand, packet $y_2$ is transmitted from node 8 to 7, since the channel is conflict free. Such scheduling decisions are made for all packets and nodes in the network and the state of buffers at the end of the time slot is displayed in Figure 3-5.
In the NC algorithm, the data packets from node 5 are network coded and transmitted to nodes 4 and 6 which are at one hop distance and other packets are transmitted if the channels are conflict free. This is shown in Figure 3-6. In case of the NCPC algorithm, the packets are transmitted from node 5 to nodes 3 and 7, which are at two hop distance and is displayed in Figure 3-7. Note that \( z \) represents the network coded packet \( x_1 \oplus y_1 \).

The steps 2 and 3 are repeated until the entire message exchange is complete. The exchange is completed, when the left buffer of node 1 has all left bound packets and right buffer of node 9 has all right bound packets as shown in Figure 3-8.
With this implementation, the data flow in the line network for information exchange via DF, NC and NCPC algorithms are displayed figures 3-9, 3-10 and 3-11, respectively. Note that the numbers on the right side of the figures denote the time slots. The dotted lines show the unintentional broadcast of packets to the node at the head of the dotted line. This node does not react to these unwanted packets.

Figure 3-8: Packet position on the buffers after complete message exchange

Figure 3-9: Nodes 1 and 9 exchanging 3 data packets through DF algorithm
Figure 3-10: Nodes 1 and 9 exchanging 3 data packets through NC algorithm
3-2 Results

The throughput and the associated energy cost (total energy consumed by the network) for various data transmission algorithms are presented in this section. The results were obtained by varying the number of nodes and messages in the network. Specifically four different line networks comprising of 10, 25, 40, 75 nodes are considered here. These numbers are chosen to compare the performance in reasonably increasing size of network.

3-2-1 Throughput

As explained before, transmissions and receptions are the two major operations that influences throughput and energy consumption in the network. As expected,
the total number of transmissions and receptions are reduced in NCPC compared to NC algorithm. The total number of transmissions and receptions for different algorithms DF, NC and NCPC are shown as a function of number of messages in Figures 3-12 and 3-13.

![Figure 3-12: Total number of transmissions in the network for exchanging up to 30 messages in a line network of 10 nodes using different data transmission algorithms](image1)

![Figure 3-13: Total number of receptions in the network for exchanging up to 30 messages in a line network of 10 nodes using different data transmission algorithms](image2)

This resulted in an improved throughput as shown in Figure 3-14. The total number of timeslots taken for a complete message exchange is determined. This is then used to derive the throughput of the network which is inversely proportional to the number of time slots. In Figure 3-14, the curves represent the total number of time slots required for the exchange of different number of messages. The three curves in each graph corresponds to three different data transmission algorithms – DF, NC and NCPC. The lesser the time slots taken the better throughput. From the Figure 3-14 it is clear that the NCPC algorithm gives better throughput compared to NC and DF algorithms. The reason is clearly due to the increase in transmission...
range by power control along with network coding operations in several nodes of the network.

![Figure 3-14: Timeslots as a function of the number of messages exchanged in a network of 10, 25, 40 and 75 nodes. The lesser the timeslots taken, better the throughput.](image)

### 3-2-2 Energy consumption

In this section, we see the energy cost (total energy consumed by the network) required to increase the throughput in the network. The total energy consumed by the network for complete message exchange using different algorithms is computed using the energy model explained in Section 2-5. For the given number of nodes and messages, the total number of transmissions, receptions and data processing operations (XOR) are obtained using the C program described above. The total energy consumption for different algorithms is then computed as follows.

\[
E_{DF} = N_t \cdot (E_{tp} + E_c) + N_r \cdot E_r 
\]  

(3-1)

\[
E_{NC} = N_t \cdot (E_{tp} + E_c) + N_r \cdot E_r + N_p \cdot E_p 
\]  

(3-2)

\[
E_{NCPC} = N_{t1} \cdot E_{tp} + N_{t2} \cdot E_{tp2} + (N_{t1} + N_{t2}) \cdot E_c + N_r \cdot E_r + N_p \cdot E_p 
\]  

(3-3)

where \( E_{DF}, E_{NC} \) and \( E_{NCPC} \) are the total energy consumed by the network using DF, NC and NCPC algorithms respectively. \( N_t, N_r \) and \( N_p \) denote the total number
of transmissions, receptions and XOR operations performed by the nodes in the network. In DF algorithm, $N_p = 0$ as the costs associated with network coding are not incurred. The transmit power for one hop distance transmission range is $P_t$. In NCPC algorithm, the transmit power $P_{t2}$ is used when transmission range is increased to two hop distance and $E_{tp2}$ is the corresponding transmission energy. In NCPC, the total number of transmissions using different transmit powers $P_t$ and $P_{t2}$ are $N_{t1}$ and $N_{t2}$ respectively.

The assumption here is that the nodes are equi-distant to each other. To compute total energy in NCPC we make use of Friis equation, which relates the transmit power to the range. The equation can be written as,

$$ P_r = P_t G_t G_r \left(\frac{\lambda}{4\pi d}\right)^{\eta} \quad (3-4) $$

where $P_r$ is the received power with certain SNR, $P_t$ the transmit power radiated by the antenna, $G_t$ and $G_r$ the transmit and receive antenna gains, $\lambda$ the wavelength of communication signal, $\eta$ the path loss coefficient and $d$ the distance between transmitter and receiver. We consider a free space for the analysis and therefore path loss exponent $\eta$ is equal to 2. This implies that the transmit power has to be increased by a factor of four to double the transmission range. This relation is used in transmission energy computation, when the range is increased, or when power is controlled. From this it follows that $E_{tp2} = 4 \times E_{tp}$ in equation 3-3.

As explained earlier, the total number of transmissions and reception for message exchange in the network determines the total energy consumption in the network. In Figure 3-15 we show the number of transmissions and receptions that are reduced by using NCPC compared to NC algorithm.

![Figure 3-15: Total number of transmissions and receptions that are reduced in NCPC compared to NC for exchanging up to 30 messages in a line network of 10 nodes](image)

The number of transmissions and receptions that are reduced are about 19% and 28% respectively. We can now compute the the amount of energy conserved when using NCPC. For the purpose, the total energy consumption in the network is
computed for various values of $E_r$, $E_c$ and $E_p$. We begin by considering the most simple case, eventhough this is unrealistic. We assume that the costs $E_r$, $E_c$ and $E_p$ to be negligible. We shall use practical values later in this chapter. Under the zero costs case, the transmission energy $E_{tp}$ is the dominant factor in the total energy consumption in the network. Even when the total number of transmissions and receptions that are reduced in the network is high compared to total number of transmissions at higher transmit power, when $E_{tp}$ is dominant, then the total energy cost to maximize throughput using NCPC technique is high compared to NC technique. From this, it follows that using lower transmit powers gives energy conservation in the network. This is further seen in Figure 3-16. The total energy consumed in the network is much higher for NCPC algorithm compared to NC and almost equal to DF algorithm due to use of higher transmit power.

![Figure 3-16: Total energy consumption (in terms of $E_{tp}$) when $E_c = E_r = E_p = 0$](image)

However, in reality the costs associated with reception of data $E_r$ and hardware operation $E_c$ are usually not negligible. Therefore, we now we study the total energy consumption in the network when $E_r$, $E_c$, $E_p$ and $E_{tp}$ are all comparable. The total energy consumption in the network is computed in units of the transmit energy $E_{tp}$ and the resulting curves are in Figure 3-17.

Based on the curves in Figure 3-17, we conclude that NCPC is useful when total energy consumed due to the increase in transmission range is less than the total energy saved from reduced number of transmissions and receptions. This condition is met when $E_c = E_r = E_p = E_{tp}$.

We refine the assumption above to include practical hardware. In practice the values of $E_c$, $E_r$, $E_p$, $E_{tp}$ are not identical. Real-world values are taken from a widely used
radio transceiver CC2420 [26]. In this chip, it is seen that \( E_r \) is dominant compared to \( E_c \) and \( E_{tp} \). Moreover, \( E_{tp} \ll E_c \). In other words, the hardware cost, \( E_c \) and \( E_r \) dominates the total energy budget significantly. Therefore, based on the above discussed results, it appears that NCPC reduces total energy cost in the network compared to NC and DF techniques. In other words, transmitting at higher transmit power is advantageous since the total number of transmissions and receptions are reduced which in turn reduces the total energy consumption in the network. This is further verified using the energy values obtained from a real hardware in the following section.

**Energy consumption in a practical hardware - a case study**

In this section, the total energy consumed by these three algorithm from a typical lab measurement is presented. We use \( E_{tp} \), \( E_r \), \( E_c \), and \( E_p \) consumed for different operations by an energy harvesting sensor, comprising of a micro-controller – MSP4301611 and radio – CC2420 for the purpose\(^1\). In the experiment, the time was divided in slots of duration 2 seconds. In a given time slot, a node can transmit, receive or remain in low power mode (LPM) or sleep mode. The size of the data packet is 128 bytes. Therefore for a data rate of 250kbps, the time taken to transmit or receive a data packet is 4ms. In the remaining time, the node is in LPM.

The following are the energy costs expressed in milli-joules pertaining to the above

\(^1\)These energy values are based on the measurements carried out at the Zenlabs, CEDT, IISc, India
mentioned hardware.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Energy (mJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{tp} + E_c$</td>
<td>0.3</td>
</tr>
<tr>
<td>$E_{tp2} + E_c$</td>
<td>0.4</td>
</tr>
<tr>
<td>$E_p$</td>
<td>0.007</td>
</tr>
<tr>
<td>$E_r$</td>
<td>0.3</td>
</tr>
<tr>
<td>LPM</td>
<td>0.7</td>
</tr>
</tbody>
</table>

With these values, the total energy consumed by the network through different algorithms is shown in Figure 3-18. The graph implies that the NCPC consumes less energy when compared to NC and DF algorithms.

**3-2-3 Summary**

Based on the above observation, the performance in terms of throughput and energy conservation of NCPC technique can be summarized as follows.

1. The total number of transmissions and receptions are reduced due to joint network coding and power control operation in the network compared to NC
technique. The reduction is about 19% for transmissions and 28% for receptions. This in turn reduces the total number of time slots (about 10%) required for message exchange in the network resulting in increased throughput. Therefore throughput is always higher for NCPC technique compared to the NC and DF techniques.

2. In some of the widely used radio chips, CC2420, CC1000 [31], $E_c$ and $E_r$ are greater than $E_{tp}$. For such hardware, NCPC reduces total energy consumption in the network compared to DF and NC. This result is in agreement with [31] in which an optimal transmit power that minimizes total energy consumption for data transmission in a line network is computed. In otherwords, using higher transmit power for single hop transmission is better using lower transmit powers and multi hop data transmission, which is also evident from the above analysis.

With this we conclude that for typical hardware configurations, NCPC technique maximizes throughput at less energy cost (total energy consumption in the network) compared to NC and DF techniques.
In the previous chapter it was found that NCPC offers better throughput and energy conservation in a network of nodes with limited energy and/or with nodes harvesting energy at a low rate. In realistic EH networks, the energy availability within a node and across the EH network varies over time. In this chapter the focus is on the application of joint Network Coding and Power Control (NCPC) in varying energy environment. To do so, we classify the energy pattern across the network and propose a power control algorithm that adapts to the varying energy as well as create additional network coding opportunity in the network.

4-1 Energy patterns in EH networks

The amount of harvested energy in an EH node depends on the efficiency of EH source. Moreover, each node in the network has its own energy harvesting opportunity. This leads to varied energy availability across the network. By energy pattern we refer to the energy state of all nodes across the network at the given time. We classify the energy patterns as moderate, abundant or varied based on the following energy harvesting scenario. As an illustration, we consider a solar energy based EH-WSN with several nodes.

- Moderate energy pattern: This is when all nodes in the network have moderate amount of energy stored or energy harvested is at a low rate. This situation would arise when the nodes do not harvest energy due to the absence of sunlight. Energy conservation is essential in this case. Hence, low power consumption techniques pertaining to battery operated WSNs can be used for EH-WSNs. The NCPC algorithm studied in Chapter 3 is applicable here, because the total number of transmissions and receptions are reduced in several nodes (compared to DF and NC techniques) resulting in energy conservation in the network.
- **Abundant energy pattern**: This is when every node in the network has abundant energy harvested for a certain duration. This happens when all nodes exposed to direct sunlight, and the ones in the shade have conserved energy over a period of time and has abundant energy. When there is a surplus of energy, an efficient way of utilizing that energy is by doing certain operations that improve system throughput. Hence we consider a power control algorithm in addition to NCPC explained in Chapter 3 that varies transmission range in such a way that more coding opportunity is created in the network which in turn improves throughput. This is further elaborated later in this chapter.

- **Varied energy pattern**: This is when each node in the network has different amount of harvested energy. The energy states of nodes in the networks can be either abundant, moderate or insufficient. Such a pattern can be observed when the nodes in direct sunlight have better harvesting opportunity compared to the ones in the shadow. This may give rise to a situation where some nodes (the ones in the shade) harvest insufficient energy to perform data transmission operation. When data is routed via these nodes, communication is temporarily suspended. In order to sustain communication, a technique to control power which in turn alters the transmission range is required. Therefore, an adaptive power control method along with network coding operation can be used to increase the throughput of the network. This is further explained in the later part of the chapter.

- The above energy patterns lead to a worst case scenario in which several consecutive nodes in the route run short of energy. The communication is suspended until the next energy harvesting opportunity. Since we restrict our analysis to a maximum of two-hop distance transmission range, when two or more consecutive nodes in the line network run short of energy the transmission is suspended until next energy harvesting opportunity.

### 4-2 Power Control in EH networks

In order to handle the varying energy level within an EH node as well as across the network as explained above, we consider power control that varies the transmission range in EH networks. This also means that the decision to control power depends on the energy availability in an EH node and across the network. One of the efficient ways of utilizing the varying energy in an EH node is by setting several energy thresholds and defining operations a node can perform for these thresholds. We define three energy regions in the storage device of an EH node – *bare minimum energy, moderate energy, abundant energy*. The corresponding energy levels are defined to be $E_0$, $E_1$, $E_2$ and $E_{max}$ as shown in Figure 4-1.

The energy between $E_0$ and $E_1$ is *bare minimum energy* which is required for the system to be up and running. If the available energy in a EH node is $E_a$, and if $E_a \leq E_1$, then the node is in sleep mode. Moreover, it is essential to meet the condition $E_a \not\leq E_1$. This is because, there can be a significant amount of energy...
wastage to turn on the system once it is completely shut down [32]. Hence when the energy level is in the moderate region, which is between $E_1$ and $E_2$, several low power consumption techniques are essential. The NCPC technique explained in Chapter 3 can be used here. When $E_a > E_2$, the objective is to increase transmit power and therefore the transmission range. The additional power control to vary transmission range along with NCPC is then applicable in this case.

### Power control algorithm

Before we explain data transmission in different energy pattern, here we present a power control algorithm that can be executed at the node level to adapt to the varying energy pattern. The following power control algorithm can be executed by the EH nodes based on energy availability in the node and its neighbours. The different operational states an EH node goes through based on the energy availability in the node and its neighbours in a one time slot is depicted using a state flow diagram as shown in Figure 4-2.

It has been assumed that a node can be in sleep or wake mode in a given timeslot. In wake mode a node can transmit or receive a single data packet and goes to sleep state. From sleep mode, the node goes to wake state when it has packet to transmit or receive. In a given timeslot, if an intermediate node $n$ has a packet to transmit, node $n$ performs several energy checks to determine the transmission range before transmitting the data packet. At the beginning of every time slot, node $n$ checks its own energy level $E_a$. If $E_a \leq E_1$, then the node enters sleep mode. If $E_a$ falls under moderate energy region then the transmission range is set to one hop distance and only when the node $n$ does not perform network coding. The transmission range is set to two hop distance otherwise. The node $n$ also learns the energy level of the neighbour that receives data packet. If the corresponding neighbour node(s) runs short of energy to receive data packet, then the node $n$ suspends data transmission and enters sleep mode. If $E_a$ is in abundance, then the node learns the energy availability status across the route. We assume that the node learns the energy availability across the network using one the algorithms proposed in [12], [15], [33]. If all nodes in the route have abundant energy, then the node performs power control in such a way that it creates network coding opportunity. This is further explained in Section 4-3-2 with an illustration. If the node detects that the nodes are at different energy levels, then the node sets the transmission range to two hop
distance if the corresponding neighbour node has energy to receive data packet, otherwise the transmission range is set to one hop distance. If the neighbour node at one hop distance runs short of energy to receive data packet, then the node suspends data transmission and enters sleep mode. After data transmission the node enters sleep mode until the next data transmission or reception opportunity.

4-3 Data transmission algorithm

The throughput and energy consumption of the network is computed using the data transmission protocol explained in Section 3-1. The power control technique explained in the above section is added to this algorithm in order to handle the varying nature of harvested energy. A logical point to perform the energy checks
in data transmission protocol is during scheduling, which is when the active links for data transmissions in the network are determined. The performance of NCPC over DF is analyzed for different energy patterns considered. From this the overall performance of NCPC can be determined.

4-3-1 Moderate energy across network

The different data transmission techniques explained in chapter 3 are applicable in this case. In Chapter 3, it is found that the NCPC technique gives better throughput compared to DF and NC techniques. It has also been showed that the energy cost for practical hardware is less for NCPC compared to DF and NC.

4-3-2 Abundant energy across network

The power control technique along with NCPC and DF are illustrated using an example. Consider a network comprising of 11 nodes, each in abundant energy state for a certain duration. The number of nodes is chosen arbitrarily. In simple DF technique, each intermediate node forwards the data packet to the neighbour located at two hop distance. Moreover, the end nodes alter the transmission range between one and two hop distance for alternate messages in order to balance the data traffic across the network. For instance, if message $x_1$ is handled by nodes 2, 4, 6, etc., then message $x_2$ should be handled by nodes 3, 5, 7, and so on. This way higher efficiency in utilizing the harvested energy is achieved across the network. The data flow in the network on the execution of data transmission algorithm along with power control for DF is as shown in Figure 4-3.

In NCPC technique, power control is done in such a way that it creates additional coding opportunity across the network. Therefore the intermediate nodes check for network coding possibility at its neighbour nodes before deciding a transmission range. The following algorithm is specific to a line network and for a simple message exchange.

1. The end nodes alter the transmission range between one and two hop distances for alternate messages as in DF technique. This is shown in Figure 4-4, and in timeslots 1 and 3 for messages $x_1$, $x_2$, $y_1$ and $y_2$.

2. In addition, the intermediate nodes check the buffer status of their neighbours to decide the transmission range. For instance, if an intermediate node $n$ has a left bound packet to transmit and if its neighbour node $n - 1$ has a right bound packet in its right buffer and $n - 2$ has an empty buffer or packet with highest sequence number (compared to the packet in $n - 1$) in its right buffer, then the transmission range is set to one hop distance. This is further shown in Figure 4-4, in time slot 5 where the nodes 5 and 9 sense network coding opportunity at nodes 4 and 10 respectively and therefore set the transmission range to one hop distance.
Figure 4-3: Data transmission using simple data forwarding along with power control technique during abundant energy in the network.

Figure 4-4: Data transmission using network coding along with power control technique during abundant energy available in the network.

3. If node $n$ senses no network coding opportunity both at $n-1$ and $n-2$, then the transmission range is set to two hop distance. This is observed in all
timeslots except timeslot 5 in Figure 4-4.

This algorithm has been used to compute throughput for line networks containing different number of nodes and compared with DF technique. The time taken for exchanging five packets of message in line networks containing 11, 15 and 21 nodes were computed manually and are given in Table 4-1.

<table>
<thead>
<tr>
<th>Nodes</th>
<th>DF</th>
<th>NCPC</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>28</td>
<td>22</td>
</tr>
<tr>
<td>15</td>
<td>34</td>
<td>26</td>
</tr>
<tr>
<td>21</td>
<td>37</td>
<td>32</td>
</tr>
</tbody>
</table>

Table 4-1: Time taken (in terms of timeslots) for 5 packets of message exchange

From the above Table 4-1, it is clear that NCPC using this power control technique gives better throughput compared to DF along with power control.

4-3-3 Varied energy case

Here we again consider a case of varied harvested energy across a network of 11 nodes as shown in Figure 4-5. We assume that the nodes 3, 5, 10 in the line network have insufficient energy (highlighted in red) to perform any operation and remains in sleep mode. In order to sustain communication, we assume the corresponding neighbour nodes 2, 4, 6, 9 and 11 have abundant energy harvested (highlighted in green) in the figure 4-5. The remaining nodes in the network are assumed to have moderate energy (highlighted with yellow).

In DF technique, the intermediate nodes with abundant energy set the transmission range to two hop distance and ones with moderate energy set to one hop distance. The data flow in the network on the execution of data transmission algorithm along with power control for DF is as shown in Figure 4-5.

In NCPC, the intermediate nodes that perform network coding operation or have abundant energy set the transmission range to two hop distance provided the corresponding neighbours have sufficient energy to receive data packet. The nodes with moderate energy that do not perform network coding operation set the transmission range to one hop distance. The data flow in the network on the execution of data transmission algorithm along with power control for NCPC is as shown in Figure 4-6.
Figure 4-5: Data transmission using simple data forwarding along with power control by nodes in the network having varied harvested energy.

Figure 4-6: Data transmission using network Coding along with power control by the nodes in the network having varied harvested energy.
4-4 Performance of NCPC

The throughput and energy consumption in the network are computed for the above illustrated scenarios. The results of NCPC are compared with the existing data transmission technique DF.

**Throughput** – The throughput in terms of total number of time slots taken to exchange two data packets for the above explained scenarios is shown in Table 4-2.

<table>
<thead>
<tr>
<th>Technique</th>
<th>Moderate</th>
<th>Abundant</th>
<th>Varied (without PC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DF</td>
<td>21</td>
<td>13</td>
<td>14</td>
</tr>
<tr>
<td>NCPC</td>
<td>14</td>
<td>11</td>
<td>12</td>
</tr>
</tbody>
</table>

Table 4-2: Time taken (in terms of timeslots) for 2 packets of message exchange

The total number of time slots required to exchange data packets using NCPC is lesser than DF for all energy patterns in an EH network. This is because, the total number of transmissions and receptions are reduced due to network coding and power control operations performed by several intermediate nodes. This eventually reduces the total number of time slots required for message exchange and therefore increases the overall throughput compared to DF along with power control technique.

**Energy consumption** – The total energy consumed by the network is computed using the energy model explained in Section 2-5. The total energy consumed by NCPC and DF techniques for various energy patterns and for different values of $E_c$, $E_p$, $E_r$, and $E_{tp}$ are given in the following tables.

<table>
<thead>
<tr>
<th>Technique</th>
<th>Moderate</th>
<th>Abundant</th>
<th>Varied</th>
</tr>
</thead>
<tbody>
<tr>
<td>DF</td>
<td>40</td>
<td>76</td>
<td>72</td>
</tr>
<tr>
<td>NCPC</td>
<td>40</td>
<td>59</td>
<td>59</td>
</tr>
</tbody>
</table>

Table 4-3: Energy consumption (in terms of $E_{tp}$), when $E_c = E_p = E_r = 0$

<table>
<thead>
<tr>
<th>Technique</th>
<th>Moderate</th>
<th>Abundant</th>
<th>Varied</th>
</tr>
</thead>
<tbody>
<tr>
<td>DF</td>
<td>120</td>
<td>120</td>
<td>120</td>
</tr>
<tr>
<td>NCPC</td>
<td>104</td>
<td>107</td>
<td>107</td>
</tr>
</tbody>
</table>

Table 4-4: Energy consumption (in terms of $E_{tp}$), when $E_c = E_p = E_r = E_{tp}$

<table>
<thead>
<tr>
<th>Technique</th>
<th>Moderate</th>
<th>Abundant</th>
<th>Varied</th>
</tr>
</thead>
<tbody>
<tr>
<td>DF</td>
<td>80</td>
<td>46</td>
<td>50</td>
</tr>
<tr>
<td>NCPC</td>
<td>60</td>
<td>44</td>
<td>46</td>
</tr>
</tbody>
</table>

Table 4-5: Energy consumption (mJ), for energy harvesting sensor using micro controller – MSP4301611 and radio – CC2420

The energy values in tables 4-3, 4-4, 4-5 shows that NCPC technique reduces the
overall energy consumption in the network compared to simple DF technique. Further by means of adaptive power control the energy at node level is also conserved. The following can be observed from the energy values in tables 4-3, 4-4, 4-5.

- The power control along with network coding technique gives energy savings compared to only power control and DF. This is true for all cases where total energy consumption in the network by NCPC is lower than the power control in DF technique.

- When the energy due to hardware cost $E_c$ or reception energy $E_r$ is dominant, more transmissions at higher transmit power give overall energy conservation in the network. This is seen in Table 4-5 that the energy consumption for DF in abundant case is less than NCPC in moderate energy case. This is because of the more power control operation in DF (in abundant case) compared to NCPC (in moderate case). In Table 4-5, the total energy consumption is computed energy values $E_r = 0.3\text{mJ}$, $E_p = 0.007\text{mJ}$, $E_{tp} + E_c = 0.3\text{mJ}$ (one hop), and $E_{tp2} + E_c = 0.4\text{mJ}$ (two hop). Here the hardware cost $E_c$ and reception energy $E_r$ is much greater than $E_{tp}$, and $E_{tp2}$. This is again in agreement with [31] in which the authors show that using higher transmit power for single hop transmission is better than using lower transmit powers for multi hop data transmission due to the reduction in total energy consumption by the network.

Based on the above we may conclude that network coding along with power control is beneficial in terms of throughput and energy conservation across the network compared to only network coding or only power control in data forwarding technique.
Conclusions and Future work

With advances in energy harvesting technology in sensor nodes, newer energy management techniques are rapidly emerging in order to efficiently utilize the harvested energy within an EH node and across the network. This in turn improves the system performance. The previous chapters dealt with one such emerging technique. Specifically, we explored the possibility of joint network coding and power control. This was then used to study the throughput and energy benefits it can offer for EH networks. For the purpose, we considered a simple line network in which packets generated by the end nodes have to be exchanged via the intermediate nodes. Three energy patterns moderate, abundant and varied were defined and a joint network coding and power control algorithm that is adaptive to the varying energy (both at node and network level) was proposed. The performance of NCPC is compared to two other data transmission techniques – simple data forwarding (DF) and network coding (NC) techniques.

5-1 Conclusions

The two main operations that influence throughput and energy consumption in a multi-hop network are transmissions and receptions. A reduction in the total number of transmissions and/or receptions can improve data throughput in the network. Network coding minimizes total number of transmissions in the intermediate nodes that combine packets and send in a single transmission. This increases overall throughput while simultaneously conserving energy in the network. Another way to reduce transmissions and receptions is by transmitting data at a node at a larger distance by increasing the transmission range. In other words, performing a single long hop transmissions instead of several multi-hop transmission is advantageous. This is because single-hop transmission minimizes total number of transmissions and receptions in the network and therefore maximizes throughput. But this comes with an energy cost at the node. In EH networks, although energy conservation is
Conclusions and Future work

essential for perpetual operation of EH node, this is not as critical as in battery operated devices. This is because the energy within the individual EH nodes may increase or decrease while in battery operated devices, the residual energy decreases monotonically. Even when a EH node has zero residual energy and shuts down, the node is restarted at the next energy harvesting opportunity. This motivates the use of power control to increase the transmission range in EH networks.

In the case of moderate rate of harvested energy across the network, transmitting power is controlled only in nodes that perform network coding. The total transmissions and receptions are therefore reduced and the overall throughput is improved compared to NC and DF techniques. However, energy conservation is achieved only when the total energy consumed by increasing the transmit power is less than the energy saved from the reduction in total number of transmissions and receptions. This condition is attained when $E_c$, $E_r$ and $E_{tp}$ are comparable. However, in reality these values may not be identical and in practical applications that use CC1000 and CC2420 radio transceivers, NCPC is better than NC.

In the abundant and varied energy cases, the transmission range is based on the energy state of the node and its neighbours. In addition, the network coding possibility at the neighbour nodes is taken into account. We then compared the throughput to that obtained by power control in DF technique. Our finding is that NCPC gives better throughput and energy conservation when compared to DF with power control. Energy is conserved for all energy values, because of the network coding operation and the reduction in transmissions. Moreover, by means of power control, the varying energy is managed efficiently and the throughput is maximized along with network coding operation.

The conclusion is of this work is that power control is suitable in EH networks for sustained operation of the network. Adaptive power control along with network coding improves throughput in line network while conserving energy in typical hardware configurations.

5-2 Future work

This work is an initial study of NCPC in EH networks. The following are the immediate tasks that need to be addressed for the completeness of our work.

Analysis of error scenarios: We considered an ideal channel model with a reliable data delivery. In a realistic channel, interference and fading can cause reception of incorrect data and packet loss that demands retransmission of data packets. This affects the overall throughput and total energy consumption in the network.

Simulations or practical experiments: The performance of NCPC in different energy patterns is analyzed for a simple line network. This needs further analysis through simulations or practical experiments for different number of nodes and message exchanges. Moreover, the power control algorithm executed at the node level to adapt to varying energy pattern has to be analyzed over highly varying
energy patterns in the network. Also, the energy consumption due to the overhead of control messages need to be taken into account.

**Higher transmission range:** In this thesis, the power control to a maximum transmission range of two hop distance has been considered. An increase in transmission range may further improve throughput. However this consumes more energy at node level but can be considered for scenarios with abundant energy across network.

**Realistic network:** The case of power control in order to create network coding opportunities where energy consumption is not a constraint, can be further studied for a more realistic topology like rectangular grid or mesh networks. Such algorithms can be used to optimize or improve several other performance metrics like reduction of data queuing, delay, etc.

**Cross layer approach:** The joint network coding and power control technique can be integrated with other energy management techniques like harvested energy aware routing and adaptive duty cycling to improve system performance further in practical applications.


