Abstract - To avert the fore-coming energy crunch, LTE devices should be made capable of not just saving but also harvesting energy from their surroundings. Energy saving mechanisms like the Discontinuous Reception (DRX) Scheme are already in use, there still needs to be development and design of energy harvesting modules. This paper focuses on designing a scheduling scheme for battery powered mobile devices with energy harvesting capability by leveraging the DRX mechanism built in LTE. Simplistic energy harvesting model is proposed in a two way LTE-A communication system. The results are obtained by performing simulation in the NS3 environment with various cases.

I. Introduction

In the recent years, energy harvesting has become an area of keen interest for designers and researchers. Harvesting energy, in essence is amassing of readily available energy. This energy may be a byproduct or a clean source such as sunlight. This energy is converted to electrical energy and is made use of in the device served by the harvester. The idea is to have a connected society in which to connect with one another all like sensors, cars, drones, medical and wearable devices will use cellular networks, interacting with human end-users to provide a series of innovative services such as smart homes, cities, and cars [4]. To serve this ambitious vision, the future networks need to magnify the current capacity at-least a 1000x. Current architectures increase capacity by scaling up the transmit power. Given the forecast, that by 2020, there will be more than 50 billion connected devices, scaling up transit powers is not sustainable. That is, using more and more energy to increase capacity is not economically viable. Carbon based energy sources currently power up the communications system. At present, information and communication technology (ICT) systems are responsible for 5% of the world’s CO2 emissions [2]. The percentage is increasing rapidly as the number of connected devices are increasing. Therefore, there is a need to avert the energy crunch, that energy saving and energy harvesting can achieve.

In LTE enabled User Equipment(UE), there exists a power saving mechanism called the Discontinuous Reception (DRX) scheme [3, 7, 12]. In the target networks, the key mechanism to allow UE hardly any power consumption without penalizing the Quality of Service(QoS), i.e., delay is the ability to predict when UE will be asleep and on contrary when it can be awake [5, 6]. Now, clearly DRX saves energy consumption but there is also a need for maintaining a healthy charge in the batteries. A clean way to recharge the UE batteries is to employ energy harvesting from its surroundings. Mahdavi-Doost et al. [10] considered the problem of downlink scheduling in an LTE network powered by energy harvesting devices. They designed the optimization problem for maximizing all considered energy efficiency metrics over an energy harvesting LTE downlink. In [9], a novel energy harvesting DRX mechanism is proposed to minimize the device wakeup delay while keeping the energy consumption in cellular networks for IoT devices. This paper takes into consideration the use of solar energy which is the most common kind of harvested energy.

The results are obtained by carrying out simulations in the NS3 simulator with different real world scenarios. The paper is organized as follows. Markov model for energy harvesting is described in Section II and Simulation model is presented in Section III. In addition, the simulation results are presented and discussed in Section IV. Section V compares the results obtained when DRX Mechanism is present in the UE and when it is the removed. Further, the paper is concluded in Section VI.

II. Markov Model

The harvester serves the UE’s by adding the charge to their respective batteries. The harvester assumes to harvest sunlight, and also the simulation assumes to work in sunlight all the times.

A UE is said to be operational if the amount of the remaining energy in its battery exceeds a particular threshold. On contrary, if the remaining energy falls below this threshold, it becomes non-operational and hence is not participating in the network. Futher, in energy harvesting environments, a UE is charging when the amount of energy collected is larger than the consumed energy; otherwise, it is discharging. Consequently, depending on its operational state (i.e., ON, OFF) and the amount of the collected energy from the ambient environment (i.e., Charging, Discharging) a UE can be in four different states and is presented in Table I [8].

The state of UE which is operational, and its battery is charging (described by State 1) and is represented by (1). Similarly, the state of UE that is operational, and its battery is discharging (described by State 2) and is represented by (2). The state of UE that is non-operational, and its battery is charging (described by State 3) and is represented by (3). The state of UE that is non-operational, and its battery is discharging (described by State 4) and is represented by (4). Figure 1 shows the state transition diagram for the Markov chain.
It is observed from Figure 1 that the transition probabilities $p_{43}$ and $p_{41}$ can be omitted because an operational UE whose battery is being charged (i.e., ON-C) is not expected to transit directly to a non-operational state (i.e., OFF-C, OFF-D). Similarly, the transition probabilities $p_{41}$ and $p_{43}$ can also be omitted, as UE being in a non-operational state and whose battery is discharging (i.e., OFF-D) first needs to collect a certain amount of energy in order to become operational again. In addition, UE that is operational and its battery is discharging (i.e., ON-D) is not expected to become non-operational and charge its battery (i.e., OFF-C) directly, thus $p_{23}$ and $p_{22}$ can be omitted.

Let $\alpha$ be the probability when UE’s battery is charging and $\beta$ be the probability that UE’s battery is discharging, and it is expected to stay in the particular state. Let $\gamma$ denotes the probability moving from the state 2 to the state 1. Let $P$ be the one-step transition probability matrix of this four state discrete time Markov chain [8].

$$P = \begin{pmatrix}
\alpha & 1-\alpha & 0 & 0 \\
\gamma & \beta & 0 & 1-\beta-\gamma \\
\gamma-\alpha & 0 & \alpha & 1-\gamma \\
0 & 0 & 1-\beta & \beta
\end{pmatrix}$$

We know that the transition probabilities lies in between 0 and 1. Therefore, $0 < 1-\beta-\gamma < 1$ and $0 < \gamma - \alpha < 1$ or $\gamma < 1-\beta < 1+\gamma$ and $\alpha < \gamma < 1+\alpha$ . It follows that $\alpha < \gamma < 1-\beta$.

Assume that $\pi_1, \pi_2, \pi_3, \pi_4$ denote the steady state probability of the UE being in state ON-C(1), ON-D(2), OFF-C(3), OFF-D(4), respectively. Let $\pi = (\pi_1, \pi_2, \pi_3, \pi_4)$. Solving $\pi P = \pi$ with $\sum_{i=1}^{4} \pi_i = 1$. We obtain,

$$\pi_1 = \frac{(1-\beta)^3(\gamma-\alpha)}{(2-\alpha-\beta)((1-\beta)(\gamma-\alpha) + (1-\alpha)(1-\beta-\gamma))}$$

$$\pi_2 = \frac{(1-\alpha)(1-\beta)(\gamma-\alpha)}{(2-\alpha-\beta)((1-\beta)(\gamma-\alpha) + (1-\alpha)(1-\beta-\gamma))}$$

For the derivation, refer Appendix.

III. Simulation Model

The following subsections discuss the topology created in the simulation environment and the steps required as per the model to obtain the results.

A. Topology of the Network

Figure 2 shows the network topology for the simulation. The eNB (Evolved Node B) is the hardware that is connected to the mobile phone network that communicates directly wirelessly with mobile handsets (UE’s). The topology makes use of the LENA (LTE+EPC) module of the NS3 simulator. In the LTE-EPC architecture two eNB nodes and two UE’s are used. Each UE is connected to a respective eNB node and is kept stationary.

![FIG. 2: The network topology for simulation](image-url)
area $10^{-3}m^2$ is 14.9695. Further, it is assumed that the average time for which the harvester is ON is 4.5ms. The assumption is based on the fact that the long cycles and short cycles have a listening period of 4.5 (average).

B. Simulation steps for Energy Harvesting

The following are the brief steps of the carried out simulation [11]. The simulation is carried out with the scenarios mentioned in Section IV.

1. Create the PGW Node using EPC helper of NS3.
2. Create a single remote host.
3. Create the internet and install it on the remote host, and connect the host to the PGW node.
4. Create the UE and eNB nodes and install LTE module on them.
5. Assign a constant mobility model to the UE and eNB nodes. Connect the UEs to the eNB nodes.
6. Create a socket on UE devices to monitor packet traffic.
7. Create MyApp application which contains the DRX scheme.
8. Create Energy Harvester application and install it on both the UE’s.
9. Set the efficiency of harvester and battery used. Also set the parameters of the harvester.
10. Take an average of the two harvested and total energies of the two UEs.

IV. Simulation Results

The simulation runs for 20 seconds. The UEs communicate via the DRX mechanism with each other and therefore consume energy. Depending on the scenario in which the harvester is turned on the harvested energy is calculated. Note the results are from a linear model where the harvested energy is calculated and made use at the end of the simulation. The stochastic model suggested can be a part of future work.

The following subsections discuss the various scenarios of the harvester sensor as real world applications. Namely, sensor is turned on only when the RRC is on (i.e., Case I), sensor is turned on periodically (i.e., Case II) and sensor is always on (i.e., Case III).

A. Case I

Energy is harvested by the harvester only when the RRC is turned ON, or the short-cycle/long-cycle is in its listening period. For instance in the real world it is impractical to keep the sensors for harvesting on at all times. This may lead to more energy consumption than saving. Hence, when the RRC is turned on only then the sensors are turned on. Table II illustrates the energy consumed and energy harvested taking some combinations of values of number of short and long cycles in simulation.

<table>
<thead>
<tr>
<th>Number of short cycles</th>
<th>Number of long cycles</th>
<th>Energy consumed ($\mu J$)</th>
<th>Energy harvested ($\mu J$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>4674.97</td>
<td>141.72</td>
</tr>
<tr>
<td>0</td>
<td>20</td>
<td>866.14</td>
<td>174.995</td>
</tr>
<tr>
<td>20</td>
<td>0</td>
<td>1909.03</td>
<td>663.388</td>
</tr>
<tr>
<td>20</td>
<td>40</td>
<td>1215.82</td>
<td>425.238</td>
</tr>
<tr>
<td>40</td>
<td>60</td>
<td>1455.91</td>
<td>562.506</td>
</tr>
<tr>
<td>40</td>
<td>80</td>
<td>1455.49</td>
<td>562.506</td>
</tr>
</tbody>
</table>

Table III represents energy consumed and energy harvested varying the number of short cycles while keeping length of long cycles (40) and inactivity timer (.05s) fixed.

<table>
<thead>
<tr>
<th>Number of short cycles</th>
<th>Energy consumed ($\mu J$)</th>
<th>Energy harvested ($\mu J$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>846.376</td>
<td>175.671</td>
</tr>
<tr>
<td>10</td>
<td>942.634</td>
<td>327.306</td>
</tr>
<tr>
<td>20</td>
<td>1215.82</td>
<td>425.238</td>
</tr>
<tr>
<td>40</td>
<td>1455.99</td>
<td>562.506</td>
</tr>
<tr>
<td>50</td>
<td>1547.01</td>
<td>626.382</td>
</tr>
<tr>
<td>60</td>
<td>1592.1</td>
<td>661.94</td>
</tr>
<tr>
<td>80</td>
<td>1634.01</td>
<td>695.261</td>
</tr>
</tbody>
</table>

FIG. 3: Trend of Harvested and Consumed energy in varying number of short cycles
From Figure 3, it can be verified that as the number of short cycles increases the energy consumed and energy harvested also show a marked increase.

Table IV represents the energy consumed and energy harvested varying the number of long cycles while keeping the length of short cycles and inactivity timer fixed.

**TABLE IV: Varying the number of long cycles**

<table>
<thead>
<tr>
<th>Number of long cycles</th>
<th>Energy consumed(μJ)</th>
<th>Energy harvested(μJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1901.03</td>
<td>663.385</td>
</tr>
<tr>
<td>10</td>
<td>1294.71</td>
<td>442.919</td>
</tr>
<tr>
<td>20</td>
<td>1215.82</td>
<td>425.238</td>
</tr>
<tr>
<td>40</td>
<td>1215.82</td>
<td>425.238</td>
</tr>
<tr>
<td>60</td>
<td>1215.82</td>
<td>425.238</td>
</tr>
</tbody>
</table>

FIG. 4: Trend of Harvested and Consumed energy in varying number of long cycles

From Figure 4, it can be verified that as the number of long cycles increases the energy consumed and energy harvested also show a decrease to some extent and after that they become almost constant.

**TABLE V: Varying the length of inactivity timer**

<table>
<thead>
<tr>
<th>Length of inactivity timer(ms)</th>
<th>Energy consumed(μJ)</th>
<th>Energy harvested(μJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>448.599</td>
<td>908.013</td>
</tr>
<tr>
<td>5</td>
<td>425.238</td>
<td>1215.82</td>
</tr>
<tr>
<td>10</td>
<td>406.388</td>
<td>1469.69</td>
</tr>
<tr>
<td>15</td>
<td>385.323</td>
<td>1662.52</td>
</tr>
<tr>
<td>20</td>
<td>372.835</td>
<td>1898.33</td>
</tr>
</tbody>
</table>

FIG. 5: Trend of Harvested and Consumed energy in varying the inactivity timer

From Figure 5 it can be verified that as the length of inactivity timer increases, the energy consumed decreases but the energy harvested shows an increase.

**B. Case II**

Case II discusses the contrary scenario to Case I. That is, instead of the harvester being on only when RRC is turned on. Here the sensor is turned on periodically independent to the RRC for energy harvesting.

Table VI represents the values of energy harvested and energy consumed varying the length of periods in which energy is being harvested.

**TABLE VI: Varying the period of turning on the harvester**

<table>
<thead>
<tr>
<th>Period(s)</th>
<th>Energy consumed(μJ)</th>
<th>Energy harvested(μJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0001</td>
<td>1215.82</td>
<td>162596</td>
</tr>
<tr>
<td>0.001</td>
<td>892.177</td>
<td>16270.3</td>
</tr>
<tr>
<td>0.01</td>
<td>1005.66</td>
<td>1621.68</td>
</tr>
<tr>
<td>0.1</td>
<td>1455.99</td>
<td>154.67</td>
</tr>
<tr>
<td>0.2</td>
<td>1455.99</td>
<td>84.586</td>
</tr>
<tr>
<td>0.5</td>
<td>1372.38</td>
<td>32.83</td>
</tr>
</tbody>
</table>

It can be clearly observed from Figure 6 that with increasing the length of the periods the harvested energy reduces drastically. This is intuitive since the harvester is ON for a lesser time the energy harvested is also decreasing.
FIG. 6: Drastic decrease in harvested energy as the period increases

C. Case III

It can be considered when the harvester is ON at all the times which can be considered a special case of Case II with step size 0.0001 as a decent approximation. That is, the harvester sensors are turned on at periodic intervals of time. The caveat being that interval is so small that for simulation and practical purposes it behaves as though it is turned on at all times.

V. Energy Harvesting vs DRX Mechanism

In section IV, simulation results are obtained when the DRX mechanism is present in the UE for communication. However, if we remove the DRX and assume the harvester follows Case I, then the consumed energy becomes 4674.97μJ due to the fact that now no energy is being saved by the DRX mechanism. Further, the harvested energy is observed to be 162596μJ. Comparing the results, we see that the harvested energy also increases drastically since now this becomes similar to Case III.

VI. Conclusion and Future Work

This paper focuses on designing a scheduling scheme for battery powered mobile devices with energy harvesting capability by leveraging the DRX mechanism built in LTE. In conclusion, energy harvesting shows great promise. It is a clean and cheap source of energy that could cut down running costs. Further in the domain of LTE-A networks energy harvesting could be the solution to heavy battery usages of UEs. LTE-A has support already for DRX and coupled with a harvesting mechanism as such will make the device self-sufficient in energy transactions.

Furthermore, there is still ongoing research on how to harvest the energy from radio waves which are present due to so much technology in the environment. Harvesting radio waves could be the next step to increase the efficiency of harvested energy as compared to 14.95 efficiency of a typical solar cell. Both methods can be coupled up, giving rise to a multi-harvesting environment.

Appendix

Solving $\pi P = \pi$ with $\sum_{i=1}^{4} \pi_i = 1$,

\begin{align}
\alpha \pi_1 + \gamma \pi_2 + (\gamma - \alpha) \pi_3 = \pi_1 \\
(1 - \alpha) \pi_1 + \beta \pi_2 = \pi_2 \\
\alpha \pi_3 + (1 - \beta) \pi_4 = \pi_3 \\
\pi_1 + \pi_2 + \pi_3 + \pi_4 = 1.
\end{align}

From Equations (1), (2) and (3)

\begin{align}
\gamma \pi_2 + (\gamma - \alpha) \pi_3 = (1 - \alpha) \pi_1 \\
(1 - \alpha) \pi_1 = (1 - \beta) \pi_2 \\
(1 - \beta) \pi_4 = (1 - \gamma) \pi_3.
\end{align}

Now, we set $\pi_2, \pi_3$ and $\pi_4$ as functions of $\pi_1$,

$$
\pi_3 = \frac{(1 - \alpha) \pi_1 - \gamma \pi_2}{\gamma - \alpha}
$$

$$
\pi_2 = \frac{(1 - \alpha) \pi_1}{1 - \beta}
$$

$$
\pi_4 = \frac{(1 - \alpha) \pi_3}{1 - \beta}
$$

$$
\pi_3 = \frac{(1 - \alpha) (1 - \beta - \gamma) \pi_4}{(1 - \beta) (\gamma - \alpha)}
$$

$$
\pi_2 = \frac{(1 - \alpha) \pi_1}{1 - \beta}
$$

$$
\pi_4 = \frac{(1 - \alpha)^2 (1 - \beta - \gamma) \pi_1}{(1 - \beta)^2 (\gamma - \alpha)}
$$

Substituting (5), (6) and (7) in (4), we get

$$
\pi_1 = \frac{(1 - \beta)^2 (\gamma - \alpha)}{(2 - \alpha - \beta)((1 - \beta)(\gamma - \alpha) + (1 - \alpha)(1 - \beta - \gamma))}.\n$$
Hence, from (5), (6) and (7),

\[
\pi_2 = \frac{(1 - \alpha)(1 - \beta)(\gamma - \alpha)}{(2 - \alpha - \beta)((1 - \beta)(\gamma - \alpha) + (1 - \alpha)(1 - \beta - \gamma))}
\]

\[
\pi_3 = \frac{(1 - \alpha)(1 - \beta - \gamma)(1 - \beta)}{(2 - \alpha - \beta)((1 - \beta)(\gamma - \alpha) + (1 - \alpha)(1 - \beta - \gamma))}
\]

\[
\pi_4 = \frac{(1 - \alpha)^2(1 - \beta - \gamma)}{(2 - \alpha - \beta)((1 - \beta)(\gamma - \alpha) + (1 - \alpha)(1 - \beta - \gamma))}
\]

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REFERENCES