Performance Evaluation for Energy-Harvesting Machine-Type Communication in LTE-A System

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Abstract—To explore the energy efficient Machine-Type Communication (MTC) for 5G cellular systems, we developed a simulation platform to investigate the complete uplink procedures of energy-harvesting MTC devices in LTE-A (Long Term Evolution Advanced) system. Though the 3rd Generation Partnership (3GPP) has worked on LTE-A cellular standards in support of MTC transmission, the standards have not taken energy-harvesting MTC devices into their scope. Energy-harvesting technology can be the candidate to support the MTC features by allowing the devices to harvest ambient energy and support their own power usage without manual upgrade. The proposed Energy-Aware LTE-A scheme, serving as power control and admission control, prevents the devices from building the network connections greedily but ending up with energy shortage and packet loss. This scheme not only can reduce the contention level of control channels but also can decrease energy wastage on network entry procedures, thereby improving the overall energy efficiency.

I. INTRODUCTION

Machine-Type Communication is an emerging technology for the next generation communication, which allows a huge number of autonomous devices to communicate with each other or with a central controller via wired or wireless connections. MTC devices are usually low power consuming. Potential MTC applications [1] include healthcare, tracking, sensor monitoring, vehicular telematics, smart grid, etc. Once the devices are deployed, they operate automatically for a long period of time without human intervention. In view of this, energy harvesting technology can be a promising technique for those devices to function permanently without battery replacement.

Energy harvesting technology not only can meet the demands of MTC applications but also can make devices cost-effective and energy-efficient. Devices with energy-harvesting modules harvest energy from external sources, such as solar energy, mechanical vibration, heat or wind [2] [3]. Energy harvesting technology then converts the harvested energy to electricity for devices’ power usage. Energy harvesting technology has shown great advance to power wireless devices in industries [4] and structural health monitoring [5], which are difficult to access after deployment.

LTE-A, which is a foreseeable widely applied next generation telecommunications standard led by 3GPP, also focuses on supporting the non-negligible trend of Machine-Type Communication. According to [6], MTC with diverse applications has explosive growth in the number of devices and the number of connections. Thus, it may cause an essential problem in radio access network [7], i.e., random access congestion. LTE-A standard began to look into overload problems in the random access network [7] [8]. However, LTE-A standard has not taken into account of energy-efficient protocol design for energy-harvesting MTC devices.

This work focuses on developing an LTE-A simulation platform with a large number of energy-harvesting MTC devices. To successfully transmit packets, these devices in the idle mode have to acquire uplink radio resources via the RACH procedure. After successfully going through the RACH procedure and NAS (non-access stratum) signalling connection, the devices are granted for the dedicated data channels to uplink packets. We study the power consumption behaviour of energy-harvesting MTC devices in each state of LTE-A system. Considering the necessary signalling information exchange in the control channel in order to gain the uplink radio resource, we propose Energy-Aware LTE-A scheme to prevent energy-harvesting MTC devices from accessing the control channels arbitrarily.

II. RELATED WORK

Random access congestion occurs when numerous MTC devices contend for random access resources. In the legacy cellular network such as GSM, UMTS, or LTE, a UE (user equipment) sends a uniformly selected preamble sequence on the random access channel to inform the base station of its connection request to uplink data. If numerous devices request for the network connection at the same time, they may transmit preambles and cause preamble collision on all available random access channels. Since the base station is unlikely to successfully decode a collided preamble, all RACH resources are blocked by those collided MTC devices and thus the QoS of human-to-human communication will be affected. Previous works have shown that without proper admission control or adaptive random access optimization, the collision may be so severe that almost all resources are wasted and no UEs can successfully establish the connection [9] [10]. To investigate RACH contention situation resulting from MTC devices, 3GPP has specified [8] to provide protocol-level simulation and evaluation. However, few literatures provide the performance evaluation for LTE-Advanced cellular system with energy-harvesting MTC devices.

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Design challenges of wireless sensor network with energy-harvesting devices are indicated in [11], including topology control, Medium Access Control (MAC), reliable data delivery, etc. Most researches focus on the design of MAC protocols for energy-harvesting devices in wireless local area networks instead of cellular networks. In [12], the authors considered a linear topology of perceptually powered data sinks and energy-harvesting sensors. They evaluated the impact of transmit power control on the wireless sensor network for railway track monitoring. An optimal energy management policy for wireless sensor network with solar-powered devices is proposed in [13] and analysed by game theory approach. DeepSleep mechanism, proposed in [14] aimed at improving the energy efficiency for IEEE 802.11 power saving mode with energy-harvesting devices. DeepSleep mechanism forces energy-harvesting devices to sleep longer so as to reduce the power consumption on idle listening and overhearing, while guarantees those devices with higher transmission priority after they wake up. [15] studies different MAC protocols including CSMA and polling techniques for wireless sensor network with energy-harvesting sensors. The proposed probabilistic polling protocol considers the unpredictability of harvested energy and achieve better performance in terms of throughput, fairness and inter-arrival times. [16] shows the cooperative data link automatic repeat request (ARQ) protocols can be applied to improve the throughput of wireless sensor network deployed with energy-harvesting sensors. In the cooperative ARQ protocols, relaying packets can be viewed as a concept of borrowing energy from one another and balancing the sensors’ energy consumption to match their own battery recharge rate.

To study the power efficiency, [14] classifies the radio interface states and uses the corresponding power consumption values to analyse the performance of IEEE 802.11 PSM with energy-harvesting devices. [17] studies the energy efficiency of WiFi, 3G and LTE network with the measured power consumption values. The authors designed a tool, 4GTest for Android, and collected the power consumption values replied by the users. However, the measured power consumption values vary with the data rate and cannot show the difference between radio interface states. In our work, we evaluate the power consumption of energy-harvesting MTC devices based on LTE radio interface states in each signalling exchange step so as to acquire the better understanding of the relationship between the energy consumption on communications and the harvested energy.

III. SYSTEM DESCRIPTION

We developed an MATLAB platform with the LTE-Advanced eNB (evolved NodeB) and thousands of energy-harvesting MTC devices described in [18]. Those devices act as environmental monitors, collect information and uplink to a central controller, which is the eNB. The data traffic of MTC applications such as healthcare monitoring, tracking and tracing is mainly uplink to a data sink, so we study the communication behaviour and power consumption of those devices for uplink data only. Those energy-harvesting devices, once deployed, harvest the ambient energy and convert them to electricity for power usage without human intervention.

We further assume the devices have already selected the desired cell after being powered up. The core network has already anchored the devices in MME (Mobility Management Entity). So, the investigated system focuses on what procedures the devices should perform when the packets arrive in buffer. The procedures of uplink data in the MATLAB platform include the idle mode, network entry and the connected mode, shown in Fig. 1. After cell selection, the devices enter the idle mode, in which the radio interfaces can be turned off for power saving. No signalling exchanges between the devices and the eNB. No uplink resources are reserved for the devices. When packets generated from the application layer arrive in buffer, the devices then turn on their radio interfaces to request uplink radio resources from the eNB.

![State Diagram for Energy-harvesting MTC Devices](image_url)

Before data transmission, the devices should first build the network connection via network entry procedures, defined as the RACH procedure and NAS signalling exchange. To complete the RACH procedure, the device should go through four-step message exchange with the eNB described in [18]. First, the device transmits the RACH preamble, selected uniformly from a pool of preamble sequences, \( R \), to the eNB. RACH preambles with different sequences can be detected by the eNB simultaneously due to their orthogonality property. However, when more than one device send RACH preambles with the same preamble sequence, those preambles collide with each other and thus the eNB cannot reply the random access response to the devices. After sending the RACH preamble, the device will set a timer, i.e., random access response (RAR) window, to wait for the expected random access response from the eNB. Upon receiving the random access response within RAR window, the devices send an RRC (radio resource control) connection request and the time alignment (TA) information together in the dedicated uplink resource (UL grant) specified in the random access response. After sending the RRC connection request, the device activates a contention resolution timer, known as mac-ContentionResolutionTimer or Msg4 timer. Finally, if the device receives Msg4 from the eNB within Msg4 timer, the RACH procedure accomplishes successfully. That is, the energy-harvesting MTC device has completed the RACH procedure and gain the uplink radio resources from the eNB.

Any failures in the four-step message exchange cause the energy-harvesting MTC devices to enter the backoff process. The failures can be resulted from no random access response within RAR window or no Msg4 reception within Msg4 timer. In the backoff process, the device uniformly selects a period of time from the window of \([1, W]\), to count down. The value of \( W \) is specified by Backoff Indicator (BI), which is assigned by the eNB through attaching a subheader to the RAR on the PDSCH (Physical Downlink Shared Channel). During the backoff process, the power consumption of the device becomes lower, and the preamble contention level is reduced as well.
After counting down, the device restarts the RACH procedure with preamble transmission as long as the number of trials is less than the maximal number of preamble transmission trials. After the devices are granted with uplink data radio resources, they establish NAS signalling connections with the core network and then enter the connected mode.

In the connected mode, the device with packets in buffer can perform uplink transmission via the dedicated uplink data channel without collision. When the packets in buffer are all transmitted, the device activates the inactivity timer. Whenever the packets arrive before the inactivity timer expires, the device transmits the incoming packets immediately, and then restarts the inactivity timer again once all packets are transmitted. If the inactivity timer expires, the devices release the uplink data radio resources within the disconnect timer. Then, they enter the idle mode, where the radio interfaces are turned off for power saving.

IV. EVALUATION METHODOLOGY
A. Energy Harvesting Model and Traffic Model

We applied Bernoulli process to model the harvested energy [19] [20] and data traffic of an energy-harvesting MTC device. [21] has shown that solar radiation can be modelled as first-order two-state Markovian model and Bernoulli process. A sequence of independently identically distributed Bernoulli trials \(X_1, X_2, X_3, \ldots, X_i\) forms Bernoulli process, where \(i\) represents the time slot index. We model the amount of harvested energy in each time slot and the amount of packet arrival as Bernoulli trials. The independent Bernoulli trials imply Bernoulli process to be memoryless. In each time slot, the device can harvest \(E_h\) energy with probability \(p_e\), and no energy with probability \(1 - p_e\). The mean of energy harvesting model is 49.19 mW. In each time slot, one packet comes to the data buffer of the device with probability \(p_t\), and no packet arrives with probability \(1 - p_t\). The mean of traffic model is 1 packet per second, which is suitable for MTC application scenarios. Table I shows the parameters of the traffic model and energy harvesting model in detail.

B. Na"ive LTE-A Scheme

We simulate LTE-A system with thousands of energy-harvesting MTC devices in the Matlab platform. The simulation platform involves the idle mode, RACH procedure, NAS signalling connections, data transmission and uplink radio resources release following [18]. In naive LTE-A scheme, the energy-harvesting MTC devices perform the original procedures defined in LTE-A system to uplink data from the idle mode to the connected mode. However, LTE-A system is designed for battery-powered devices with most of the traffic as voice call. The traffic type is quite different from that of the energy-harvesting MTC devices. If packets arrive in the buffer of devices in the idle mode, the devices will go through the control plane signalling exchange to acquire the uplink radio resources so that they can finally transmit uplink packets. The power consumption to gain the uplink resource is inevitable but quite high compared to the amount of harvested energy. Therefore, we propose Energy-Aware LTE-A scheme to control the energy usage of the energy-harvesting MTC devices, referred to Algorithm 1.

Algorithm 1 Energy-Aware LTE-A Scheme

1. if in idle mode and packets in queue then
2. if \(E \geq E_{\text{aware}}\) then
3. turn on radio interface
4. perform the RACH procedures for data transmission
5. else
6. the radio interface is off for power saving
7. end if
8. end if

C. Energy-Aware LTE-A Scheme

In Energy-Aware LTE-A scheme, the devices in the idle mode should be aware of their energy level to decide whether to enter the network entry procedures right away. Instead of often encountering energy shortage and wasting energy on network entry procedures, the devices should perform network entry procedures only when they harvest enough energy to break the value of \(E_{\text{aware}}\) shown in Table I, which is designed by the balanced policy.

Lemma 1. By following the balanced policy, the value of \(E_{\text{aware}}\) enables the energy-harvesting MTC devices to harvest sufficient energy for transmission of all queued packets when the connection establishment completes.

Proof: If the device is not able to transmit all its queued packets due to energy shortage, the packets will be queued until the next connection establishment completion. Without the appropriate energy control, the device will keep encountering the energy shortage. Thus, the queue length keeps increasing, causing packet loss. The goal of the balanced policy is balancing the long-term averaged harvested energy and energy consumption to decrease packet loss due to energy shortage. In the balanced policy, the appropriate energy threshold \(E_{\text{aware}}\) is found based on the average time period between two connection establishments, \(T_{\text{con}}\). The expected number of arrival packets during \(T_{\text{con}}\) is \(T_{\text{con}} \times p_t\). The required energy, \(E_{\text{out}}\), to transmit all these packets is expressed as \(E_{\text{out}}(T_{\text{con}}) = E_{\text{RACH}} + E_{\text{con}} \times T_{\text{con}} \times p_t\), where \(E_{\text{RACH}}\) is assumed to be the energy consumption on connection establishment without retransmission. \(E_{\text{con}}\) is assumed to be the energy consumption on transmitting one packet. From the energy harvesting model, the harvested energy during \(T_{\text{con}}\) can be computed as \(E_{\text{in}}(T_{\text{con}}) = p_e \times E_h \times T_{\text{con}}\). Based on the balanced policy, \(T_{\text{con}}\) is found by \(E_{\text{in}}(T_{\text{con}}) = E_{\text{out}}(T_{\text{con}})\). Hence, \(T_{\text{con}} = \frac{E_{\text{con}}}{p_e \times E_h \times p_t}\) and the corresponding energy threshold of the balanced policy is \(E_{\text{aware}} = p_e \times E_h \times T_{\text{con}}\).

D. Simulation Setting

In the beginning of the simulation, all energy-harvesting MTC devices are in the idle mode, where the devices have already completed cell selection. Upon packet arrival, the devices start to do network entry procedures for uplink transmission resources. After successful RACH procedure, the devices perform NAS signalling exchange with the MME within the NAS signalling duration, and then they can enter the connected mode to uplink data. If the inactivity timer expires, the devices disconnect to the eNB within the disconnect timer and go back to the idle mode for power saving. The slot time is set to be 5
ms based on the setting of PRACH (Physical Random Access Channel) configuration 6 in [8]. The total simulation duration is set to be 1000 sec. Table I shows the parameter settings.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slot time</td>
<td>5 ms</td>
</tr>
<tr>
<td>Preamble sequences, ( R )</td>
<td>54</td>
</tr>
<tr>
<td>RAR window</td>
<td>5 ms</td>
</tr>
<tr>
<td>Msg4 timer</td>
<td>50 ms</td>
</tr>
<tr>
<td>Backoff Indicator, ( W )</td>
<td>20 ms</td>
</tr>
<tr>
<td>Preamble transmission retry limit</td>
<td>9</td>
</tr>
<tr>
<td>NAS signalling duration</td>
<td>60 ms</td>
</tr>
<tr>
<td>Inactivity timer</td>
<td>50 ms</td>
</tr>
<tr>
<td>Disconnect timer</td>
<td>20 ms</td>
</tr>
<tr>
<td>Simulation duration</td>
<td>1000 sec</td>
</tr>
<tr>
<td>Traffic model</td>
<td>Bernoulli process</td>
</tr>
<tr>
<td>Energy model</td>
<td>Bernoulli process</td>
</tr>
<tr>
<td>( p_s = 0.005 ), mean = 1 packet/sec</td>
<td></td>
</tr>
<tr>
<td>( E_{\text{Aware}} )</td>
<td>44 mJ</td>
</tr>
<tr>
<td>Data buffer</td>
<td>20 packets</td>
</tr>
</tbody>
</table>

Based on the communication properties, the power consumption of the energy-harvesting devices can be classified into four categories in Table II. We refer [14] for the power consumption parameter settings based on the radio interface status, shown in Table II. Only in the idle mode, the radio interface can be turned off for power saving. In other situations, the radio interface is always turned on for transmission, reception or being inactive. For example, the power consumption of data transmission and preamble transmission is classified to be Transmission state. The power consumption of counting down the inactivity timer is considered to be Inactivity state.

<table>
<thead>
<tr>
<th>State</th>
<th>Definition</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmission</td>
<td>The radio interface is on and transmitting</td>
<td>550 mW</td>
</tr>
<tr>
<td>Reception</td>
<td>The radio interface is on and receiving</td>
<td>250 mW</td>
</tr>
<tr>
<td>Inactivity</td>
<td>The radio interface is on, no transmission and no reception</td>
<td>200 mW</td>
</tr>
<tr>
<td>Idle mode</td>
<td>The radio interface is off</td>
<td>40 mW</td>
</tr>
</tbody>
</table>

V. PERFORMANCE EVALUATION

Based on the evaluation methodology, the characteristics of the control plane and data plane are comprehensively considered, including network entry procedures, application layer packet delay, packet loss and energy efficiency.

First of all, we evaluate the preamble transmission success probability and the network entry success probability in the control channels. Because of the restricted preamble sequences, if the number of devices to do network entry increases, the preamble collision probability is supposed to rise, leading to lower preamble transmission success probability, shown in Fig. 2(c). In LTE-A system, successful preamble transmission, as a initial step, does not guarantee a device to acquire the dedicated data channel. The device should go through the complete network entry process and signalling exchange to build the network connection. Without appropriate power control, successful preamble transmission may still end up with high probability of network entry failure, shown in Fig. 2(d). The reason could be that the devices in the naïve LTE scheme encounter energy shortage in the network entry process. Energy-Aware LTE-A scheme not only prevents the energy-harvesting MTC devices from greedily entering the network and wasting energy on the network process, but also serves as an admission control mechanism to increase the successful preamble transmission probability and successful network entry probability by reducing the number of devices to contend uplink radio resources.

The energy efficiency is also significantly improved by Energy-Aware LTE scheme, shown in Fig. 2(e). Once the devices gain the dedicated data channel in the connected mode, continuous data transmission is possible if the devices still have sufficient energy. Building network connection from the idle mode is like a bottleneck in the cellular system, which not only consumes high power but also may introduce a large amount of delay to successfully transmit the first packet in buffer. However, if the network connection can be built successfully, the devices with enough harvested energy can transmit the buffered packets continuously. That is, one of the available methods to improve energy efficiency is reducing the energy consumption on the control plane and utilizing the dedicated resources in the data plane.

In Fig. 2(a), the application layer packet delay of naïve LTE-A scheme is calculated by the few successfully transmitted packets shown in Fig. 2(e), thereby the variance is high. That is, once the devices are short of energy, naïve LTE-A scheme cannot allow them to harvest and save enough energy for network entry requirement. These devices are backlogged in the idle mode. The application layer packet delay in Energy-Aware LTE-A scheme is roughly 5 minutes, which is usually tolerant in the MTC application scenarios. This phenomena is caused by the balance between the traffic arrival rate and energy harvesting rate. Fig. 2(b) shows that the application layer loss is explicitly improved. Thus, Fig. 2(a) and Fig. 2(b) suggest that Energy-Aware LTE-A scheme sacrifices the tolerant delay with improved packet loss and enhanced reliability.

The outage probability, defined as the time duration when devices with packets in buffer are in the idle mode divided by the total simulation time, indicates that the energy-harvesting MTC devices are backlogged in a low power consumption state on fully harvesting energy instead of communications with the networks. In Energy-Aware LTE-A scheme, the outage probability is less shown in Fig. 2(f). It means that setting \( E_{\text{Aware}} \) to make devices spend time on saving and harvesting sufficient energy before communicating with the network will not increase the outage probability.

To sum up, the network entry success probability, the energy efficiency, the application layer packet loss and the outage probability of Energy-Aware LTE-A scheme are superior to that of naïve LTE-A scheme. Harvesting and storing sufficient energy in low power consumption mode before performing network entry process is essential, especially in LTE-A system, which requires heavy control signalling exchange before successful data transmission.

VI. CONCLUSION

To gain insights for 5G communications, we investigated the comprehensive procedures in LTE-A system for the energy-harvesting MTC devices to upload data. We considered the power consumption based on the radio interface states in
the signalling exchange process. In LTE-A system with both control and data planes, saving and harvesting sufficient energy before doing network entry is quite essential to guarantee enough energy for data transmission. Considering both the property of energy harvesting technology and the high power consumption in the control channel, Energy-Aware LTE-A scheme, as a power control and admission control mechanism, shows superior network performance and energy efficiency by wisely managing the power usage of the energy-harvesting MTC devices.

ACKNOWLEDGEMENT
This work was also supported by National Science Council, National Taiwan University and Intel Corporation under Grants NSC102-2911-I-002-001 and NTU103R7501.

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Fig. 2: Evaluation Results