IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 7 September 2023, accepted 17 September 2023, date of publication 27 September 2023, date of current version 4 October 2023.

Digital Object Identifier 10.1109/ACCESS.2023.3320070

RESEARCH ARTICLE

Empirical Comparison of the Energy Consumption of Cellular Internet of Things Technologies

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Wayne Law is supported by an Australian Government Research Training Program Scholarship.

ABSTRACT Today we are living in a society where an ever increasing number of devices or things are being connected to the Internet. Many of these devices are battery powered with the long term success of the business case justifying the deployment of these devices, dependent upon the ability of these devices to operate autonomously for extended periods without intervention to replace batteries. Utility companies delivering water and gas are seeking 10 year plus lifetimes from devices without a truck roll to replace batteries. The current industry understanding of the 5G technologies, NB-IoT and eMTC, is NB-IoT offers lower power consumption but there is little evidence for that belief. This paper uses standard load models to systematically investigate the energy demands of the two different radio access technologies under realistic usage patterns. The paper also investigates some key factors influencing energy consumption and whether a device could operate from an ideal 5 Wh battery for 10 years. In contributing to the field of knowledge in this area, we set out to compare 3GPP IoT radio access technologies using techniques aligned with existing 3GPP energy consumption evaluation methodologies. In adopting that approach, contrary to established industry opinions and messaging, we found when operating as an eMTC device, our radio module consumes less power than when it was operating as an NB-IoT device. Irrespective of it's operating mode, our radio module was unable to achieve a 10 year battery life from an ideal 5 Wh battery using a typical IoT traffic model. Most interestingly, we observed minimal change in energy consumption whether the payload size was 1 byte or 1400 bytes.

INDEX TERMS Internet of Things, LTE, IoT, eMTC, NB-IoT, LTE-M, 3GPP, 5G, cellular, energy, power.

I. INTRODUCTION

A. BACKGROUND

The rise in prominence of the so-called Internet of Things (IoT) where anything that can be connected, will be connected, has led to the adoption of a wide range of Low Power Wide Area Network technologies (LP-WAN) [1]. More recently those range of technologies have been increased through the standardisation efforts of the Third Generation Partnership Program (3GPP) in Release 13 by the introduction of enhanced Machine Type Communications (eMTC) and Narrow Band IoT (NB-IoT) [2].

The associate editor coordinating the review of this manuscript and approving it for publication was Adamu Murtala Zungeru.

Further, with both eMTC and NB-IoT meeting the ITU's IMT 2020 requirements for 5G massive machine type communications and being incorporated into ITU-R M.2150 [3], some operators are indicating they will continue to support these 5G technologies beyond the shutdown of their 4G networks [4]. A consequence of which, eMTC and NB-IoT are likely to be around for many years to come.

Whilst all of the competing technologies make claim to low power operation, the potential ubiquitous and global nature of 3GPP standardised technologies, able to piggyback on existing mobile broadband deployments, are of prime interest. With commercial radio modules entering the market, we saw it as an ideal opportunity to examine devices and assess the potential energy consumption of real devices under realistic usage patterns. With many available modules from a range of vendors offering multi-mode performance in their support for Extended Coverage - Global System for Mobile Communications (EC-GSM), eMTC and NB-IoT through the one module, it presents an ideal opportunity to compare the performance of these technologies delivered from the same piece of silicon [5].

B. APPROACH

Prior to the finalisation of Release 13, the 3GPP organisation prepared technical report TR 45.820 [6] comparing a number of IoT technology candidates. Specifically, Section 5.4 of that report outlined a methodology that was used as the basis to theoretically determine whether it was possible for an IoT device to operate for 10 years using primary cells of 5 WH capacity. Eg a pair of AA batteries.

Much has been written about eMTC and NB-IoT in the press and on blog sites about their low power characteristics. A consistent theme that has been coming through is that NB-IoT is more suited for low power operation although there is little hard evidence to back these claims up.

Whilst anecdotal in nature, it is possible this perception of lower power operation could be linked to the use cases each technology is used for. That is, with NB-IoT devices often deployed in support of lower data throughput use cases, it may be a case of a self fulfilling prophecy where the reason the energy consumption is perceived to be less, is because the throughput requirements are less. This was a key driver for our research, to understand through empirical measurement, whether in a real network, with a real device, using the same piece of silicon, is there any foundation for this perception.

Thus, this paper sets out to quantify the performance of a real device operating with eMTC and NB-IoT and compare those results against the theoretical modelling done by the 3GPP in Technical Report TR 45.820 [6]. Since eMTC has six Physical Resource Blocks (PRB) available to it in contrast to NB-IoT′s one PRB [7], we will also investigate the scenario where an eMTC device′s ability to rapidly send data through greater access to eNodeB resources might improve energy consumption because of the potential to complete transmission sooner. Thus, the cumulative energy consumption of sending larger volumes of data used by the eMTC and NB-IoT are also compared.

Our conclusion outlines a number of features, network configuration settings and IP transport protocol choices which if optimally selected and tuned, could further reduce the energy consumption and increase the lifetime of a cellular IoT device.

The rest of this paper is organised as follows. Section II outlines the measurement methodology. Section III presents the results of the experiment. Section IV discusses those results and Section V provides conclusive remarks and scope for future activities.

II. ENERGY CONSUMPTION EVALUATION METHODOLOGY

A. PRIOR WORK

We investigated previously published work where the energy consumption of NB-IoT was compared against eMTC.

Jörke et al. [8] relied on the power consumption stated by a manufacturer in their data sheet. Whilst not specifically called out, through reverse engineering it would seem that band 20 data was used although in the case of PSM power consumption, it appears the manufacturer's current consumption has been accidentally used as the power consumption. That is, 10uA on the data sheet became 10uW in the published work. Whether that 10 uW power value flowed through into other calculations, is unclear.

Sørensen et al. [9] mostly compared the energy consumption of a dedicated NB-IoT only radio module able to support two bands against a multi-mode NB-IoT, eMTC and EC-GSM module able to tune across 13 different bands and concluded that NB-IoT module consumed less energy than a multi-mode, multi-band module configured to support eMTC.

Hassan et al. [10] took a theoretical approach by adopting input from discussion papers submitted by Ericsson to 3GPP in support of the early data transmission feature. The data in Ericsson's discussion papers having been sourced from 3GPP TR45.820 [6] reflecting theoretical industry expectations from at that time, yet to be built devices.

Soussi et al. [11] also modelled performance based on information from published data sheets. They identify the source of their data as a radio module from the same NB-IoT family as Sørensen et al. [9]. As that module family identified only supports NB-IoT, it is unclear what radio module's data they used for eMTC.

Based on the above, we saw an opportunity to directly compare the power consumption of NB-IoT and eMTC using the very same module on an operator's network and take empirical measurements directly rather that relying on promotional data sheets or likely performance estimates.

B. REFERENCE MODEL

3GPP TR 45.820 section 5.4 [6] details an energy consumption evaluation methodology for IoT devices. The methodology outlines a piece-wise approach through which, the energy consumption of the different logical channels and User Equipment (UE) states are identified. These cumulative effects are used to determine the lifetime energy consumption for a device operating in support of a defined use case. By way of example as depicted in Figure 1, TR 45.820 illustrates an IP packet exchange in GSM with the states and logical channels identified.

We have adopted this approach and applied it to typical eMTC and NB-IoT use cases. That is, a typical IoT device will attach to the network, send data and then either enter Power Savings Mode (PSM) [12] and/or initialise

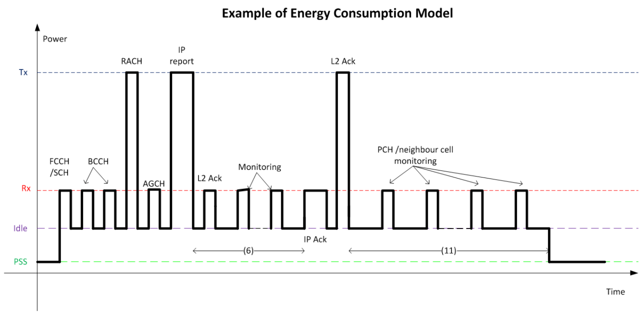


FIGURE 1. TR 45.820 energy consumption model.

extended Discontinuous Reception (eDRX) [13] depending upon the responsiveness and contactability required by the IoT application. The same device would then typically exit PSM (if that were in use) and send small messages at regular intervals. By measuring the energy consumed for each of these steps, we are able to create a piece-wise model that can be extrapolated to estimate the potential lifetime of batteries powering the device. Figure 2 illustrates the states we identified for this approach.

C. DEVICE UNDER TEST

The device used to perform our testing was a commercially available, Quectel BG96 multi-mode cellular IoT module [14]. The module supported eMTC Category M1, NB-IoT Category NB1 and EC-GSM although with 2G networks shutdown in Australia since 2016, only eMTC and NB-IoT were able to be investigated.

The BG96 was fitted to a Quectel Evaluation board [15], powered via a regulated 3.6v DC supply and loaded with Quectel firmware release version BG96MAR04A05M1GA.

D. NETWORK CONFIGURATION

We had intended to perform our test campaign at Telstra's IoT Open Lab. [16] This facility is one of a number of labs worldwide available through the GSMA's IoT Open Lab initiative. [17] Situated in Mobile Network Operator or vendor premises across the world, GSMA IoT Open Labs provide an open opportunity for researchers to access specialised technical resources both equipment and personnel that otherwise may not be possible. However, due to COVID19 lockdown restrictions and consequently closed lab facilities, the test campaign was performed over the air using Telstra's live network. A consequence of which, proximity to the nearest base station meant we were unable to assess device performance at Reference Signal Receive Power (RSRP) levels better than -85 dBm. This situation reflecting real world conditions where ordinarily many devices might not achieve coverage levels better than this anyway.

Telstra's network was selected because within Australia, they are the only operator to have deployed both eMTC and NB-IoT. Further, as they have deployed both eMTC and NB-IoT on Band 28, our testing would not be impacted by the propagation characteristics of different frequency bands. That is, Telstra hold 20 MHz of paired spectrum in band 28 onto which they have deployed LTE with a standalone NB-IoT carrier positioned in the upper guard band of that frequency holding.

TABLE 1. Network parameters.

Item	eMTC	NB-IoT
Band	28	28
Downlink EARFCN	9410	9502
DRX cycle time	320 ms	2.56 s
C-DRX	Enabled	Not enabled
PSM	Enabled	Enabled
RRC Inactivity timer	10 s	CE0 = 5 s CE1 = 10 s CE2 = 20 s

Table 1 details a few relevant network parameters from Telstra's IoT network deployment.

E. HARDWARE CONFIGURATION DETAILS

Table 2 summarises the equipment used with Figure 3 illustrating our hardware test configuration. The Device Under Test (DUT) was directly connected to the antenna via a variable attenuator enabling us to simulate a range of signal conditions.

DC power input was measured using a Nordic Semiconductor Power Profiler Kit (PPK) II [18]. The PPK2 can source and/or measure DC currents up to 1 ampere at a 100 kHz sampling rate which is more than sufficient for a cellular IoT device operating with a 1 ms Transmission Time Interval (TTI). The PPK2 connects to a host via a USB interface.

The DUT supports both a direct USB interface and a serial UART interface. To interface to diagnostics software, we used the USB interface.

We modified the baseboard of the evaluation kit to prevent current drawn by other components on the board from influencing our measurements. That is, there is a 0 ohm resistor (R104) fitted in series on the supply voltage line to the radio module. Situated in parallel to R104, J103 can be fitted with 0.1 inch pitch pins to provide a ready test connection for measuring only the current supplied to the radio module. This allows us to avoid the power disruption issues observed by Khan et al. in their empirical model. [19]

Measurement results were repeated multiple times to obtain a 95% confidence interval from a Student T-distribution with 5 degrees of freedom.

III. EXPERIMENTAL SCENARIOS AND RESULTS

We performed a range of energy consumption measurements with our device under test configured for eMTC and subsequently for NB-IoT.

A. RF POWER OUTPUT

Whilst Lauridsen et al. [20] investigated the DC input requirements across a range of RF power output measurements in a lab scenario using a base station emulator, we have not observed any comparison in literature between the Reference Signal Receive Power (RSRP) and the UE's

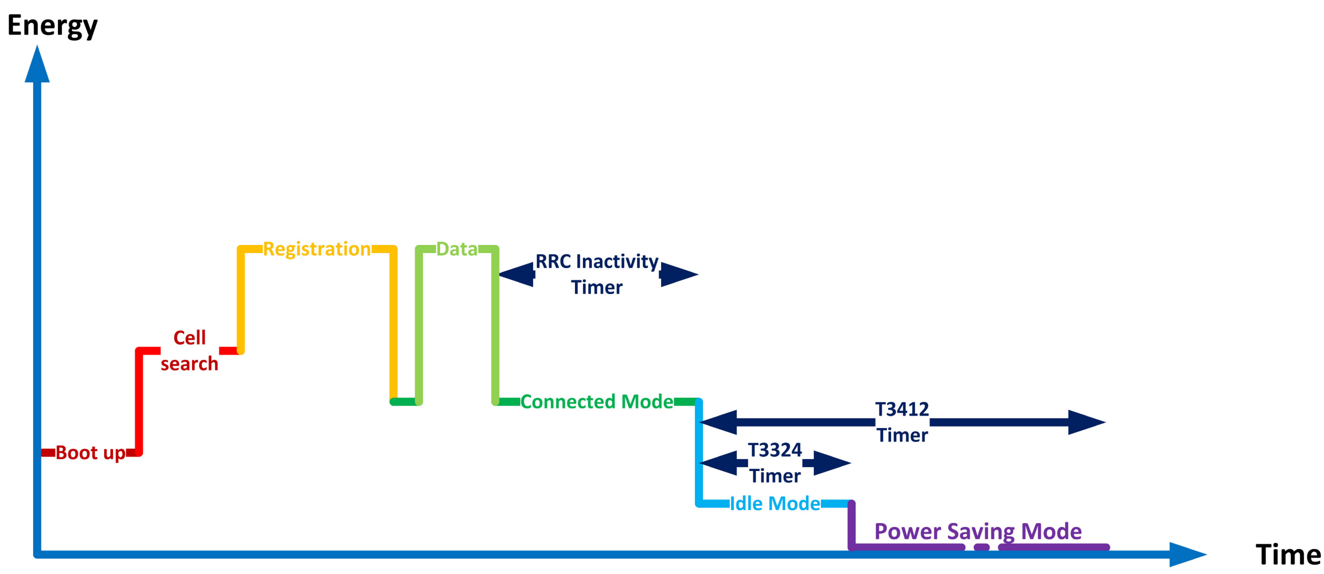


FIGURE 2. Typical IoT energy consumption model.

TABLE 2. Equipment list.

Item	Make	Model
Laptop	Dell	5420
Power meter	Nordic Semiconductor	PPK II
Evaluation board	Quectel	UMTSLTEEVB-KIT-B
Radio Module	Quectel	BG96
Attenuator	Keysight	8494A/8496A
Antenna	Quectel	YE0025AA

RF power output. That is, cellular IoT devices adjust their RF power output based upon the perceived path loss between the eNodeB and the device using the RSRP measured by the device.

As the name suggests, RSRP is a measure of the receive power of the reference signal transmitted by the base station. For many radio technologies, it is common to measure the Receive Signal Strength Indicator (RSSI). An RSSI measurement records the strength of the radio signal across the full operating bandwidth of the radio channel. For LTE, eMTC and NB-IoT, this presents a challenge because subject to traffic loading, the base station may not be using the full channel bandwidth to transmit. If the base station is not transmitting across the full channel bandwidth, then measurements taken at those times, may not provide a reliable indication of the radio signal. For this reason, RSRP is the preferred signal measure for LTE, eMTC and NB-IoT because the reference signal provides a known and dependable measure.

To obtain a plot of RSRP versus RF power output, we leveraged the diagnostic data streamed by the BG96 over USB. There are a number of ways this data can be read. With the underlying BG96 chipset (MDM9206) manufactured by Qualcomm [21], it is possible to read the diagnostics data in real time using Qualcomm's eXtensible Domain Manager (QXDM) [22] software. Alternatively, Quectel has a data logging tool Qwinlog [23] which can be used to log the diagnostic data to file for post processing using Qualcomm's Commercial Analysis Tool (QCAT) [24], QXDM, Amdoc's Actix Analyser [25] or Keysight's Nemo [26] software analysis tools.

By using QXDM and stepping the attenuator through a range of values, we were able to observe in real time the RF power output used for the Physical Uplink Shared Channel for different RSRP values. Figure 4 illustrates this relationship graphically.

Once we had completed this activity, we removed the USB diagnostics cable to prevent it from influencing subsequent power consumption measurements because like Khan et al. [19] we found the direct USB interface unfavourably contributed to our current measurements.

B. BOOTUP AND REGISTRATION MEASUREMENTS

Our initial measurements involved the powering up of the device, it attaching to the network, remaining in connected mode until suspended due to the Radio Resource Control (RRC) inactivity timer expiry and the device subsequently returning to idle mode [27]. Figures 5(a) and (b) illustrate this for eMTC at RF power outputs of +15 dBm and +23 dBm respectively.

The impact of the change in RF power output is immediately noticeable. For the specific tests illustrated in Figures 5(a) and (b), the peak DC input current when the BG96 is transmitting increases from approximately 350 mA to 600 mA although the average current only increases from 44.43 mA to 44.88 mA due to the very small duration of time the BG96 is actively sending information to the base station.

These same measurements were repeated for NB-IoT.

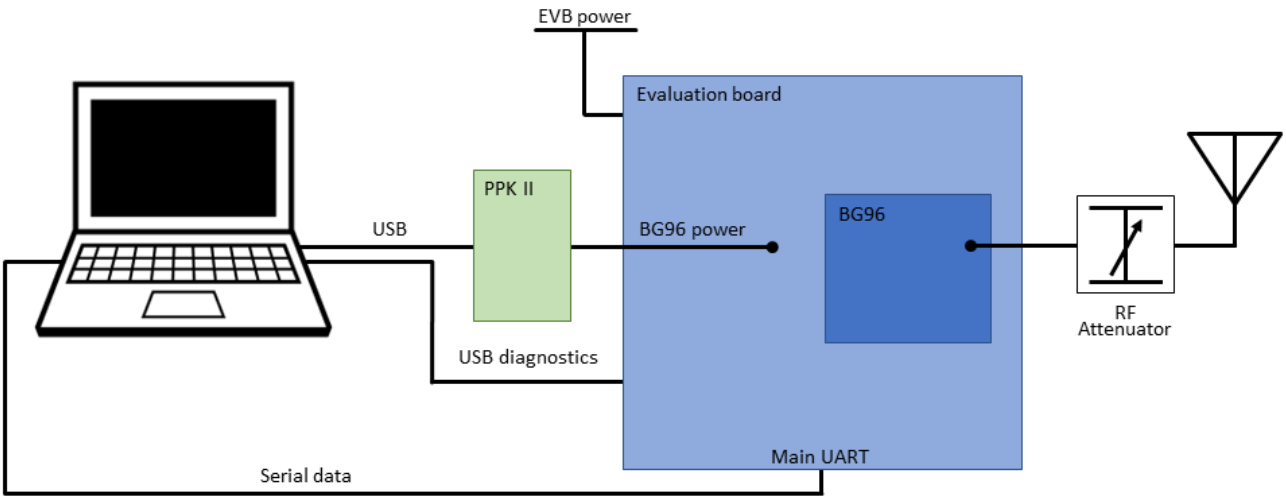


FIGURE 3. Test configuration.

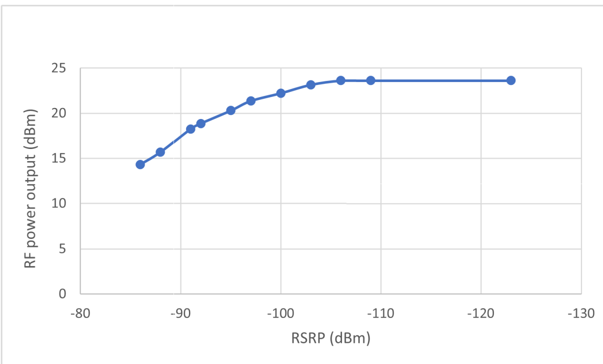


FIGURE 4. RF power output versus RSRP.

Comparing Figures 6(a) and (b), again we observed an increase in the maximum current consumption. For the specific tests illustrated, it increases from approximately 283 mA to 560 mA with a corresponding increase in average current from 47.91 mA to 49.85 mA respectively.

C. IDLE MODE MEASUREMENTS

After dropping to idle mode due to RRC inactivity, a device will remain in idle mode and monitoring the paging channel or subsequently drop to into Power Saving Mode (PSM) after expiry of the T3324 timer if PSM is enabled.

The network configured idle mode DRX cycle times for eMTC and NB-IoT are 320ms and 2.56s respectively and this can be seen in Figures 7 (a) and (b). We can expect eMTC to respond to network signalling at least 8 times quicker than NB-IoT but that responsiveness comes at a price, energy consumption. This difference in DRX cycle time is reflected in the average current consumption which was 21.1mA and 18.3mA for eMTC and NB-IoT respectively.

D. TRANSMISSION OF UDP DATA MEASUREMENTS

A typical IoT device will upload messages from time to time and more than likely will use User Datagram Protocol (UDP) due to the lower overhead this connectionless protocol affords. We investigated the amount of energy consumed in sending UDP payload sizes of 1 byte through to 1400 bytes.

Our data transmission model comprised a pair of laptop computers each running a python script to send or receive IP packets of varying size between predefined port addresses using the device under test and either eMTC or NB-IoT as the transmission medium between the two. We also repeated the tests using an uplink RF power output of +15dBm and +23dBm.

For visual comparison, the +23dBm output power level highlights the moments when the BG96 is transmitting much more clearly than the +15dBm power output level. Figures 8(a) and (b) illustrate the current consumption for 1 byte and 1400 byte payloads respectively for eMTC transmitting at +23dBm.

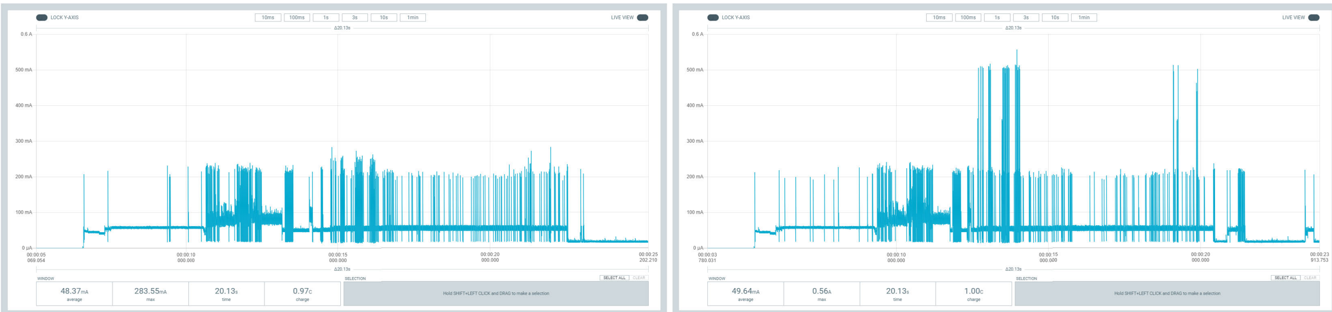
Visually the two payload sizes seem no different to one another. Each figure illustrates the device sitting in idle mode, changing state to connected mode by performing the random access procedure, transmitting the data, remaining in connected mode before again returning to idle mode after expiration of the RRC inactivity timer.

However, if we zoom in on the portion of the waveform where the payload is transmitted (the larger current spike to the left of the image centre), we see a different story.

Looking at Figure 9(a) we see the larger current spike where the BG96 transmits for a 1ms duration to send a single transport block containing our 1 byte UDP payload. In comparison, in Figure 9(b) we see the same initial single transport block sent, followed by four 3ms duration pulses because additional transport blocks are required to transmit

(a) 15 dBm output power. (b) 23 dBm output power.

FIGURE 5. eMTC boot up with C-DRX.



(a) 15 dBm output power. (b) 23 dBm output power.

FIGURE 6. NB-IoT boot up without C-DRX.

(a) eMTC. (b) NB-IoT.

FIGURE 7. Idle mode.

our 1400 byte payload along with any control plane signalling required by the network.

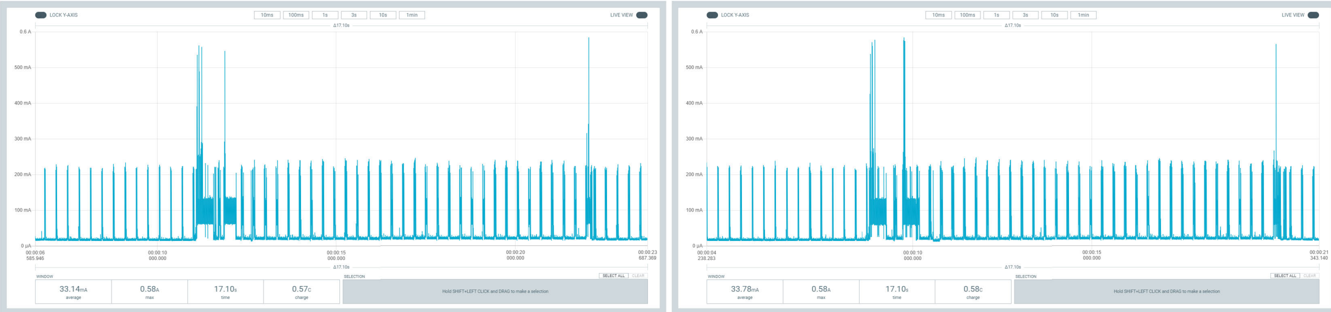
Figures 10(a) and (b) illustrate the same transmission of UDP data repeated for NB-IoT. Similar additional transport block transmission was also observed for NB-IoT in Figures 11(a) and (b).

E. TRANSMISSION OF TCP DATA MEASUREMENTS

Whilst offering a higher protocol overhead than UDP, Transmission Control protocol (TCP) based transport could potentially be used for IoT applications where it's ability to provide an ordered delivery of packets is required such as in support of Message Queuing Telemetry Transport (MQTT) [28]. Repeating the same measurements using TCP transport, we observed the current waveforms of Figures 12 and 13 for a transmit power of +23 dBm. Similar to UDP transmission, we saw an increase in the number of transport blocks sent for a 1400 byte payload compared to a 1 byte payload.

F. POWER SAVING MODE MEASUREMENTS

To minimise energy consumption, an IoT device may choose to enter PSM [29], [30], [31], [32]. As it attaches to the network, the device will signal values for two timers.



(a) 1 byte. (b) 1400 bytes.

FIGURE 8. eMTC sending a UDP payload.

(a) 1 byte. (b) 1400 bytes.

FIGURE 9. eMTC UDP transmission close up.

Specifically, timers T3324 and T3412. T3324 determines the amount of time a device will remain in idle mode and able to monitor the paging channel and hence be reachable. After this time, the network will deem the device to be unreachable and will not attempt to contact the device or forward data packets to the device. T3412 is the amount of time after which if the network has not received a Tracking Area Update (TAU) message from the device, the network will initiate detach procedures to disconnect the device. Timer T3412 includes the value of Timer T3324 so the maximum amount of time a device can stay in PSM is the difference between timers T3412 and T3324. We configured our device to enter PSM and Figure 14 illustrates the current consumption whilst the BG96 was in PSM.

G. TRACKING AREA UPDATE

We configured the device under test to enter PSM and then waited for it's T3412 timer to expire and for it to generate a Tracking Area Update (TAU). From Figures 15 (a) and (b) we can see the device awaken from the PSM state, initialise itself, reacquire the cell, transmit the TAU and then immediately drop back to idle mode. The device remained in idle mode for the duration of the T3324 timer.

H. EMTC RESULTS SUMMARY

We tabulated our results to align with our simplified model illustrated in Figure 2. Table 3 summarises these results for eMTC and NB-IoT respectively.

IV. DISCUSSION

We considered out measured results in the context of our simplified model in Figure 2

A. BOOTUP AND REGISTRATION

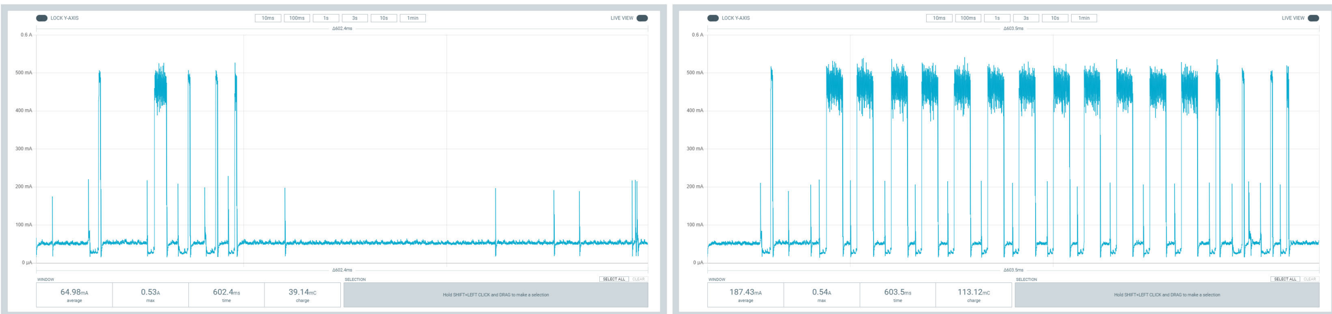
In comparing the current consumption waveforms of Figures 5 and 6, the moments when the device is transmitting are more readily visible when the RF power output is +23 dBm.

That is, from the +23dBm RF output power waveforms of Figures 5 (b) and 6 (b), we can readily identify when the BG96 is transmitting to establish an RRC connection and subsequently attach to the network and when it transmits to release that RRC connection and drop back to idle mode.

What is most interesting to note is that whilst the peak current values for NB-IoT are less than that of eMTC, the NB-IoT average current values are higher than that of eMTC. We have attributed this difference to the fact that connected mode discontinuous reception (C-DRX) was not supported for NB-IoT whereas it was supported for eMTC.

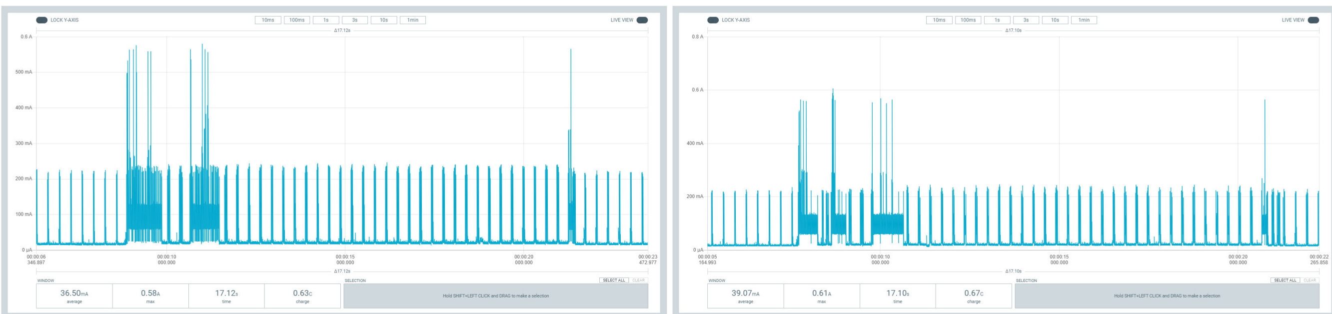
(a) 1 byte. (b) 1400 bytes.

FIGURE 10. NB-IoT sending a UDP payload.



(a) 1 byte. (b) 1400 bytes.

FIGURE 11. NB-IoT UDP transmission close up.



(a) 1 byte. (b) 1400 bytes.

FIGURE 12. eMTC sending a TCP payload.

B. CONNECTED MODE

From Table 3 we can see for the two RF power outputs measured, NB-IoT requires more input power than eMTC. It is indeed fortunate for the device using NB-IoT that the amount of time spent waiting for the RRC inactivity timer to expire is less for NB-IoT than that of eMTC. That is, the BG96 operating as NB-IoT in CE0 coverage has an RRC inactivity timer of 5 seconds whereas in eMTC mode at the same coverage levels, the RRC inactivity timer is 10 seconds. These durations are readily visible in Figures 5(b) and 6(b).

The impact of not supporting C-DRX is quite noticeable. For example, in Figures 6 (a) and (b), visually we can see a continuous average current value running through much of the waveform whereas for Figures 5(a) and (b) we only see the discrete paging time windows 320ms apart when the device consumes current to listen for paging messages. Minimal current is consumed between these paging time window intervals.

If we narrow our focus to the period when the device is in connected mode waiting for the RRC inactivity timer to expire, the average current consumed by the BG96 in eMTC mode over it's 10s wait time is 34.0mA whereas for NB-IoT during it's 5s wait interval is 52.5mA. That's a substantial reduction. C-DRX is therefore a worthwhile feature to have

(a) 1 byte. (b) 1400 bytes.

FIGURE 13. NB-IoT sending a TCP payload.

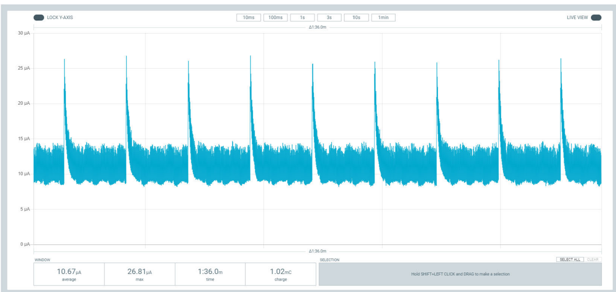


FIGURE 14. Current consumption during power saving mode.

TABLE 3. Power consumption.

	15 dBm		23 dBm	
	eMTC (mW)	NB-IoT (mW)	eMTC (mW)	NB-IoT (mW)
Bootup and registration	176	206	182	213
Connected mode	121	190	122	189
Idle mode 30 seconds	76	68	77	64
UDP transmission average	131	194	137	207
TCP transmission average	146	193	152	208
PSM 24 hours	0.039	0.039	0.039	0.039
Tracking Area Update	235	225	241	232

enabled for a device to reduce energy consumption because we can see in our case, in NB-IoT mode, the device consumes considerably more average power than when in eMTC mode.

One aspect of C-DRX we did notice is the marginal increase in latency it incurs. That is, when sending TCP data requiring acknowledgements to be sent back, those acknowledgements must wait for a paging time window to occur. In the case of eMTC, the network was configured for 320ms between paging time windows. So a longer C-DRX cycle time might incrementally reduce the average current consumption but in the case of TCP, does so by incrementally increasing latency which in turn impacts the throughput due to the transmission of acknowledgment messages.

Even with C-DRX enabled, the duration of time a device stays in connected mode has a significant impact on the energy consumption. The setting of the RRC connected mode inactivity timer is controlled by the operator's network configuration. By reducing the value of this timer, devices will reduce their energy consumption. In choosing an optimal value, operators also need to take into account the Coverage Enhancement (CE) mode [33] a device may be using.

Coverage Enhancement allows a device to operate with a greater Maximum Coupling Loss (MCL) between the UE and eNodeB. A key factor in obtaining that improvement is signal repetitions which increase the time taken to successfully transfer a message. Depending on the CE mode and the number of repetitions in use, setting the RRC inactivity timer to a smaller value may mean the timer expires before messages are successfully received because of the time required to send multiple repetitions. A means for an operator to apply different RRC connected mode inactivity timers for the different CE0, CE1 & CE2 modes, is most advantageous. Telstra's network is configured with different RRC inactivity timers for different NB-IoT CE levels as described in Table 1. Our testing was only performed using CE level 0.

Current consumption could also be reduced further through the introduction of Release Assistance Indication (RAI) [12]. RAI allows a device to signal to the network that there is no further data to send, no down link data is expected and therefore it can drop from connected mode to idle mode immediately after data transmission has concluded. In doing so the device does not need to wait for the RRC connection timer to expire. The use of RAI allows a device to control it's own destiny to some extent rather than relying on an operator's network configuration. The BG96 did not support RAI.

C. IDLE MODE

In Figures 7 (a) and (b), the differences in DRX timing is readily apparent. In Telstra's network where the I-DRX cycle times are 320ms and 2.56s for eMTC and NB-IoT respectively, for mobile terminating traffic, message latency using eMTC would be less and devices would appear more responsive. This improved responsiveness comes at a price. The average power consumption for an eMTC device is 15%

(a) eMTC.

(b) NB-IoT.

FIGURE 15. Current consumption for a tracking area update.

higher than that of NB-IoT when in idle mode due to the reduced DRX cycle timing used for eMTC.

D. TRANSPORT PROTOCOL AND PACKET SIZE

Across the range of payload sizes we tested, the average current consumed was relatively consistent and we didn't observe a substantial change from transmitting a 1 byte payload to a 1400 byte payload. In Figure 9 for example, the additional 34ms of time to send the additional transport blocks required for our 1400 byte payload over and above what was required for just a single transport block, was not statistically significant when compared to the energy required for the complete transaction. That is, 30.9mJ of energy out of an average 1.46J.

The choice of transport protocol however, did have an impact on the energy consumed. We observed an average increase in energy consumption of approximately 28% by choosing TCP over UDP. Not having to wait for packet acknowledgements, the connection-less nature of UDP allows transmission to complete sooner and energy to be saved. Noting that protocol errors with UDP would need to be resolved by higher layer application protocols and our testing did not measure this.

Examining Figure 9 (a) to send a 1 byte UDP payload we observed a single transmission of 1ms in duration. That is, a single transport block was sent. In contrast, from Figure 9 (b) for our 1400 byte payload, we observed a total of 13ms of transmission time reflecting the sending of 13 transport blocks. With an 8 byte UDP header and a 24 byte header, we require 32 bytes (256 bits) of overhead to send our payload. That is, our 1 byte payload will require 264 bits to send whereas our 1400 byte payload will require 11,456 bits to send.

For a release 13 UE, the maximum transmission block size (TBS) is 1000 bits. Looking at Tables 7.1.7.2.1-1 and 8.6.1-2 in 3GPP Technical Standard TS36.213 [34], we can see that for a TBS Index of 9 which implies a QPSK modulation scheme and using 6 Physical resource Blocks (PRB), the Transport Block Size is 936 bits. Our 1 byte payload easily fits within this transport block size and therefore a single transmission is to be expected. To send 11,456 bits for our 1400 byte payload using a TBS of 936 bits, requires a theoretical 12.24 transport blocks which is consistent with us observing 13 transport blocks being sent. Similar calculations could be performed for other payload sizes and for NB-IoT.

TABLE 4. eMTC and NB-IoT comparison.

Operating phase	Highest consumer
Bootup and registration	NB-IoT by 17%
Connected mode	NB-IoT by 56%
Sending UDP packets	NB-IoT by 50%
Sending TCP packets	NB-IoT by 35%
Power savings mode	Same
Idle mode	eMTC by 16%
Tracking Area Update	eMTC by 4%

E. POWER SAVING MODE

From Figure 14 we observed an average current consumption of 11 uA. Every 11 seconds we observed brief 24 uA pulses of current. It is unclear to us what the radio module may have been doing every 11 seconds to generate these impulsive current demands although the contribution of these impulses are included in our average current measurements.

F. TRACKING AREA UPDATES

An initial challenge we faced with configuring the device to operate in PSM mode was a random amount of time that was added to every T3412 timer request we sent. That is, to limit the perpetuation of signalling storms where multiple devices may continue to send tracking area updates at the same time until the end of eternity, the network adds a random amount of time to each T3412 value requested. For a device that awakens from PSM mode at regular interval to send data, this is not a problem. However, for us testing and trying to observe and measure a Tracking Area Update (TAU) signal, we needed to know when in time the UE would send a TAU. The 3GPP standardised AT command to configure PSM provided no feedback of the actual timer value provided by the network. We needed to use the BG96's proprietary PSM AT command to be able to see the difference between what we requested and what the network agreed to. Once we realised this, we had no problem in observing tracking area updates.

Another aspect of Tracking Area Updates is that unlike the sending of data to/from a device to the network, after sending a TAU, the UE does not need to wait for a RRC inactivity timer to expire. Instead, it immediately drops to idle mode where it will remain until any newly requested T3324 timer expires. This reduces the amount of energy consumed when no data needs to be sent with the TAU.

G. COMPARING EMTC AND NB-IOT POWER CONSUMPTION

Whilst industry and market pundits extol the virtues and lower power characteristics of NB-IoT devices over eMTC devices, our measurements did not support those lower power assertions. Indeed looking at Table 3 for the majority of measurements we took, the average power consumption of the device operating in NB-IoT mode was higher than that of eMTC. Table 4 summarises the different power consumption of each technology, eMTC and NB-IoT.

Factors influencing this outcome include the lack of C-DRX support for NB-IoT, the duration of the RRC inactivity timer and DRX timing configuration.

Observing the power consumed when the device is in connected mode waiting for the RRC inactivity timer to expire, it consumes 56% more power in NB-IoT mode than when in eMTC mode. The only saving grace is that our NB-IoT device in CE0 coverage only needs to wait 5 seconds for the RRC inactivity timer to expire whereas in eMTC mode, it has to wait 10 seconds. This increase in power consumption is due to no support for C-DRX with NB-IoT. That impact flows through into bootup and registration performance and data transmission performance affecting lifetime service life for devices powered by primary cells. By not supporting C-DRX, in a connected state, an NB-IoT device is consuming maximum power until the RRC inactivity timer expires and the device is released to idle by the network.

The settings used when the device is using DRX also impact power consumption. That is, for eMTC the DRX cycle time is 320ms in both idle and connected modes whereas for NB-IoT it is 2.56s for idle mode and not supported for connected mode. A consequence of which the device consumes 16% more power in idle mode when using eMTC. With a much reduced DRX cycle time, in eMTC mode the device would be much more responsive to downlink messaging. An operator's DRX cycle timing needs to balance responsiveness against power consumption to reflect the potential use cases each technology may be called on to support.

H. LIFETIME ENERGY CONSUMPTION

We considered a typical IoT use case where a device would attach to the network, send a small payload daily to an IoT platform, sleep for the rest of the day before waking up, sending a daily update and again returning to PSM.

With reference to our piece-wise model illustrated in Figure 2, the energy drawn by such a device over it's lifetime from day zero under ideal conditions can be approximated as

$$\begin{aligned} E_{Life} = E_{init} &\\ &+ N_{reattach}(E_{TAU} + E_{reg}) \\ &+ (N_{wakes} - N_{reattach})E_{wakeup} \end{aligned} \quad (1)$$

$$E_{init} = E_{boot} + E_{attach} \quad (2)$$

$$E_{attach} = E_{reg} + E_{tx} + E_{conn} + E_{idle} + E_{psm} \quad (3)$$

$$E_{wakeup} = E_{TAU} + E_{tx} + E_{idle} + E_{PSM} \quad (4)$$

E_{life} is the energy consumed throughout the device's lifetime,

E_{init} is the amount of energy a device expends from power up until it commences a cell search,

E_{TAU} is the energy required to send a TAU,

E_{reg} is the amount of energy expended to register to the network,

E_{tx} is the energy required to send the payload,

E_{conn} is the energy per second consumed whilst in connected mode,

E_{idle} is the energy per second consumed whilst in idle mode,

E_{PSM} is the energy per second consumed whilst in PSM mode,

$N_{reattach}$ is the number of times a device reattaches in it's life time. Our expectation is the device may attempt a TAU, realise it has failed and as a consequence, may need to reattach to the network,

N_{wakes} is the number of times a device awakens throughout it's life time. For example, if the reporting interval is daily and the device had a 3 year lifetime, it could be expected to awaken 1095 times.

Based on our measurements and the above expressions (1) - (4), with T3324 = 20 seconds, T3412 = 24 hours and only a single network attach, over a 365 day period the amount of energy consumed by our eMTC device varies between 2853 Joules and 3065 Joules with the least energy consumed when the device transmits with a UDP message at +15 dBm and the greatest amount of energy consumed when transmitting TCP at +23 dBm. NB-IoT provided similar performance with annual energy budgets of between 2973 Joules and 3094 Joules.

Industry typically talks about service lifetimes based on an idyllic 5 Wh battery. Assuming an ideal 3.6v, 5 Wh battery with 18,000 Joules of energy stored in it, the device could operate for a period of approximately 6 to 6.2 years depending on whether it is transmitting at +15dBm or +23dBm.

This is significantly different to the expectations documented in 3GPP Technical Report TR45.820 [6]

Our measurements were conducted with a radio module based on a first generation multi-mode cellular IoT chipset. We would anticipate additional optimisation activities by the manufacturer to improve performance of later generation devices. For example, the device consumes 0.039 mW of power in PSM whereas TR45.820 [6] anticipated only 0.015 mW of power. Similarly, TR45.820 assumed a 20 second time interval between the last transmission and entering PSM. During this interval of time the average power consumption we measured varied between 64mW and 77mW for NB-IoT and eMTC respectively. The latter using more power because of a lesser DRX cycle.

If we replace the values we measured for PSM and the idle period between last transmission and entry to PSM with 0.015mW and 3mW respectively from 3GPP TR45.820, we find the eMTC lifetime now exceeds 10 years and for NB-IoT, the lifetime exceeds 10 years excepting for when NB-IoT is using TCP at the maximum RF power output level of +23 dBm. In that case. the modelled lifetime is 9.43 years.

V. CONCLUSION

A. OUTCOME SUMMARY

We set out to determine whether a 10 year lifetime was achievable from an ideal 5 Wh battery. Based on our measurement regime, this would not be possible. We were able to identify deviations from the 3GPP's theoretical model which if improved, change the situation.

We were able to determine a number of areas critical to minimising energy consumption which if well managed, have the potential to improve battery lifetime.

1) Technology choice
   Contrary to popular belief, we observed NB-IoT consumed more power than eMTC. The lower speed of NB-IoT meant it took more time to send an equivalent amount of data and hence consumed more energy. The lack of support for cDRX by NB-IoT was another contributing factor.
2) Connected mode
   Maximum energy is consumed when a device is in connected mode. Consumption can be minimised by:
   - Mobile operators optimising the RRC inactivity timer
   - Support for Release Assistance Indication
   - Support for Connected Mode Discontinuous Reception
3) Protocol choice
   UDP affords lower energy consumption than TCP. For either transport protocol, our testing indicated payload sizes from 1 byte through to 1400 bytes had minimal impact on energy consumption.

B. FURTHER STUDY ITEMS

Our measurements were performed using a first generation, multi-mode module from a single vendor supporting eMTC category M1 and NB-IoT device category NB1. Areas for future study include comparison testing of a second generation device, comparison against other manufacturer's IoT products, comparison against a dedicated NB-IoT Category NB1 only device and comparison against a NB-IoT Category NB2 device.

All of our testing was performed using IP. It would be interesting to compare a similar regime of testing using Non-IP Data Delivery (NIDD) because there is much industry hype about the potential energy savings that can be realised through NIDD.

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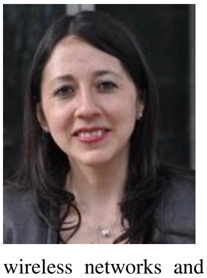

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