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Generic Energy Evaluation Methodology for Machine Type Communication

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Abstract. It is commonly accepted that the 3rd Generation Public Partnership Long Term Evolution standard is likely to be unfit for future large scale machine type communication (MMTC). As a result, a new standard, LTE Narrow-Band Internet of Things (NB-IoT) and several radio protocol proposals are being developed. One of the main performance indicators for MMTC is the radio energy consumption. It is important to be able to evaluate the energy consumption of the new standard and the proposed protocols, therefore a generic energy consumption evaluation methodology tailored for MMTC devices is required. Such methodology is the contribution of this paper. It is developed by defining a generic radio transmission and describing the factors which affect the energy consumption. Special attention is put on the factors; power control, link-level performance and a radio power model with a non-constant power amplifier (PA) efficiency model intended for MMTC devices. The results show the impact of the factors and highlight first that applying a commonly used constant radio PA efficiency model can result in an overestimation of the battery life of up to 100 % depending on the traffic scenario. It is also highlighted that combining power control, transmit repetitions and the radio power model opens for new methods to minimize the radio energy consumption.

1 Introduction

The 3rd Generation Public Partnership (3GPP) Long Term Evolution (LTE) can become unfit for large scale (massive) machine type communication (MMTC) [8,12,13,15]. As a consequence new standards are being developed, like 3GPP Narrow-Band Internet of Things (NB-IoT) and LTE for MTC (LTE-M) [1–3]. In parallel with the standardization work on NB-IoT and LTE-M, there was and still is, significant research ongoing regarding MTC protocols, as reported in [9,10,12,14]. As it is important to be able to evaluate the new standards and the proposed protocols, a generic methodology is required which is applicable for all proposed protocols and new standards.

MMTC is generally characterized as communication with infrequent small payloads, in scenarios with high device density. The devices can be in challenging

coverage conditions and have extreme battery life requirements. Therefore one of the main performance indicators for MMTC is the radio energy consumption [12].

The most common energy evaluation methodology is given in [3] and targets NB-IoT which is the state-of-the-art standard for MMTC. The common energy evaluation methodology does not include the energy consumption impact from challenging coverage conditions or the interference caused by a high density of devices. Neither does it include a realistic model of the power amplifier (PA) energy efficiency. The authors of [11] show that assuming a constant PA efficiency is not valid for smartphones from 2013-2014. Even though older smartphone radios cannot be directly compared to the radio of MMTC devices, it seems unlikely that the efficiency of an MMTC radio PA will be constant as assumed in [3].

This paper presents a generic energy evaluation methodology tailored for MMTC. The methodology includes important features for MMTC, such as uplink power control to manage the level of interference occurring from a high density of devices, transmit repetitions to cope with challenging coverage conditions, and a radio power model intended for MMTC devices. The methodology is generic through its model of a transmission. The power model is based on [3], where we propose to use a non-constant PA efficiency model intended for MMTC radios, derived from empirical measurements on smartphones [11].

The paper is organized as follows. Section 2 presents the generic energy evaluation methodology along with the revised radio power model. In section 3 we apply the proposed methodology and demonstrate the impact of its input. The results and implications of the model is discussed in section 4. The paper is concluded in section 5 which also outlines the future work.

2 Generic energy evaluation methodology

For the energy evaluation methodology to be applicable to the new standards and proposed protocols it needs to be generic. To achieve this we have identified the most important factors that affect the energy usage in a radio transmission. The identified factors are illustrated in Fig. 1. These are channel aspects such as radio fading and interference, power control, link-level performance, power model and radio access configurations such as transmit repetitions. Modelling of specific protocols which utilize several radio transmissions can be done as a chain of radio transmission blocks. The following sections will describe these factors.

2.1 Radio fading and interference

MMTC devices can experience challenging radio coverage conditions [1–3] e.g. due to being located deep indoors.

One method to overcome the effect of a large path loss is by repeating the transmissions in time [3]. When doing so, the receiver combine the received transmissions to increase the energy of the desired signal. The configuration of transmit repetitions is a part of the access configuration which also dictates

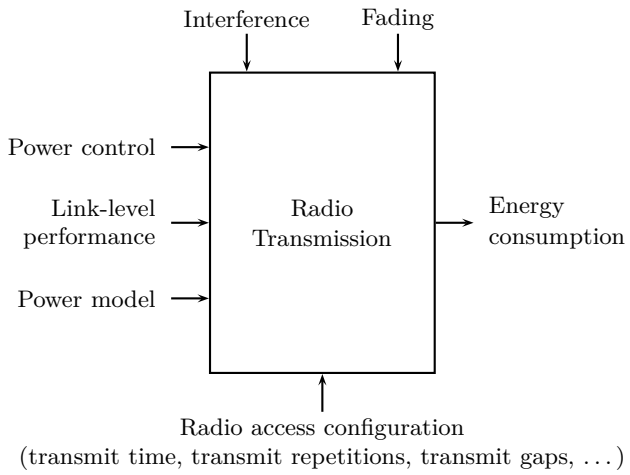

Fig. 1. Characterization of the input and outputs of a radio transmission. The inputs are power control, link-level performance, power model and the radio access configurations. The transmission is affected by interference and fading. The output is the radio energy consumption

when and how often to transmit. The number of transmit repetitions needs to be taken into account by the power control to manage the level of interference. With the use of repetitions the quantity of devices active in a single time slot (TTI) depends on how many devices start their transmission and how many are already repeating their transmissions.

2.2 Power control

In order to control the level of interference, power control is included in the methodology and for simplicity reasons open loop power control (OLPC) is chosen. OLPC targets to equalize the signal strength from the devices at the base station (BS) receiver. In the OLPC implementation, used in this energy evaluation methodology, it is chosen to use the number of simultaneous transmitting devices as the traffic intensity (M), the path loss compensation factor (α) and the target received signal strength at the BS (P_0) as the information which is broadcast to the transmitting devices. The number of active devices can be estimated by the BS through e.g. multi-user-detection techniques. The details on how this is done is out of the scope of this paper.

Each device uses the broadcast information to calculate which transmit power (Ptx) they should use. The transmit power is calculated using (1), where Ptx_{dBm} and $Ptx_{max,\mathrm{dBm}}$ is the transmit power and maximum transmit power in dBm and PL_{dB} is the path loss in dB. The devices estimate the path loss from the downlink reference received signal strength.

$$Ptx_{\mathrm{dBm}} = min(Ptx_{max,\mathrm{dBm}}, P_{0,\mathrm{dBm}} - PL_{\mathrm{dB}} \cdot \alpha) \qquad [\mathrm{dBm}] \quad (1)$$

The target received power at the BS (P_0) is determined from the desired signal to interference and noise ratio (SINR) which dictates the target performance of the transmission. The target SINR is derived from link-level performance curves, simply referred to as performance curves in this paper and are described in further detail in section 2.3. The target SINR (γ_{SINR}) can be expressed as in (2). The interference is caused by all other transmitting devices ($M-1$). The noise power is denoted by N. Notice that (2) uses the linear version of PL_{dBm} and Ptx_{dBm} and implies that all devices use the same number of transmit repetitions (R) and that it is only valid when $R > 0$, $Ptx \leq Ptx_{max}$ and as long as the path loss can be compensated.

$$\gamma_{SINR} = \frac{(Ptx \cdot PL^{\alpha}) \cdot R}{(M-1) \cdot (Ptx \cdot PL^{\alpha}) \cdot R + N} \quad [1] \quad (2)$$

2.3 Link-level performance curves

The SINR affects the receiver's probability of correctly decoding the transmitted message. By setting a target performance (e.g. 90 % successful decode probability) the corresponding target SINR (γ_{SINR}) can be found. The use of performance curves (successful decoding probability vs SINR) enable the evaluation methodology to support any coding and modulation, data type and multiple access technique with different multi user detection abilities. The corresponding SINR can be translated to SNR by considering the interference as noise.

An example of two performance curves (denoted curve A and B) are shown in Fig. 2. They are generated by a link level simulator, which simulated LTE PRACH sequences [4] (Zadoff-Chu sequences) of two different lengths. The performance shows the probability of the eNB not successful decoding the PRACH sequence at various SNR. In the figure the target performance is set to 10 % error rate which translates to a target SINR (γ_{SINR}) of -18.9 dB and -11.0 dB for curve A and B respectively. The better SINR performance of A comes at the cost of taking more time to transmit. In this example, A requires 0.8 ms (without cyclic prefix which takes 0.103 ms) and B requires 0.134 ms to transmit. The pair of a performance curve and transmit time is denoted a mode through the rest of the paper.

2.4 Power model

The radio power model used in this evaluation methodology originates from [3]. The model is updated with a PA efficiency model which is based on the work presented in [11] and modified to be used for MMTC radios. The radio power model from [3] utilizes four power states; power saving mode (PSM), receiving (RX), idle ($Idle$) and transmitting (TX). All states are included in the evaluation in order to include the energy impact of synchronization, configurations receptions, gaps between transmissions and receiving downlink traffic. A transmission with all four states (PSM, RX, $Idle$, and TX) is depicted in Fig. 3. Notice this is an example of the state order and what occurs in each state.

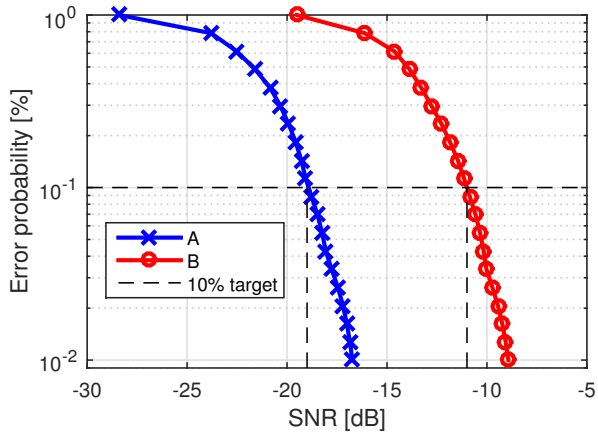

Fig. 2. Example performance curves A and B.

The transmission starts with the radio sleeping for a certain period before waking up from power saving mode (PSM). The time spend in the PSM state (T_{PSM}) depends on the traffic model, sleep configurations, and whether uplink data is ready for transmission.

Once the radio is awake it will change to RX state where it will start acquiring downlink synchronization such that it is able to decode the broadcast channel (and control channel) to receive the configuration information. This information includes power control configurations, access configurations and scheduling grants (if the protocol utilize scheduled access). If downlink data are scheduled for the device, the radio will acquire the data in the RX state. The time spend in the RX state therefore depends on whether downlink payload is available for the device, the payload size, modulation and coding and the SINR. Devices in bad coverage can be assumed to spend more time to acquire synchronization compared to others with better coverage conditions. The power consumption in the RX state (P_{RX}) is assumed, for simplicity reasons, to be independent of the modulation and coding scheme, data rate and bandwidth which is a reasonable assumption according to [11].

If the radio has uplink data to transmit, it will change to the TX state. The time spend in the TX state (T_{TX}) depends on the configured number of transmit repetitions (R), gaps between the transmit repetitions, uplink modulation and coding scheme (UL MCS) and uplink payload size. The power drawn in the transmit state (P_{TX}) depends on the transmit power dictated by the power control and the efficiency of the radio PA which similarly depends on the transmit power [11]. P_{TX} is similar to P_{RX} assumed to be independent on the modulation and coding scheme, data rate and bandwidth.

Time spend on waiting (e.g. for an opportunity to transmit uplink payload or in gaps between transmit repetitions) are spend in the $Idle$ state where the radio maintains synchronization as described in [3]. This is the main difference between

Idle and PSM, where the radio in PSM is turned off such that synchronization cannot be maintained.

The power draw in the PSM state (P_{PSM}) and the *Idle* state (P_{Idle}) are device specific.

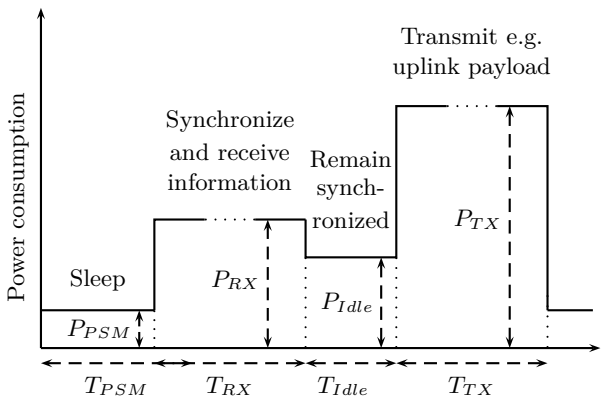

Fig. 3. Power model states (PSM, RX, *Idle* and TX) in a power and time domain with examples of what happens in each state.

The energy consumption of a transmission can be calculated as the area below the line in Fig. 3. The model proposed in this paper is given by (3). Notice that it does not consider ramp up or ramp down in state transitions like [11].

$$\begin{aligned} E_{tot} = {} & P_{PSM} \cdot T_{PSM} + P_{RX} \cdot T_{RX} \\ & + P_{Idle} \cdot T_{Idle} + P_{TX}(Ptx_{\mathrm{dBm}}) \cdot T_{TX} \end{aligned} \quad [\mathrm{J}] \quad (3)$$

The energy efficiency of the radio PA dictates the relation between the transmit power (Ptx) and the consumed power (P_{TX}). A common model from [3] assumes that the energy efficiency is constant at either 30 % or 40 % for the entire transmit power range. A study conducted by [11] shows that this is not the case for LTE smartphones in 2013-2014.

The research done in [11] might not be directly applicable in terms of absolute power values in a power model intended for MMTC devices. Clearly the best fitting PA energy efficiency model would be derived from emperical measurements from a MMTC device using NB-IoT or LTE-M radios. But as no such is commercially available (to the best of the authors' knowledge) the work presented in [11] is used to create the PA efficiency model intended for MMTC radios.

One of the targets for NB-IoT and LTE-M is low cost [3]. If the PA should be cheap and the bandwidth is lower (eg. from 20 MHz in LTE to 1.4 MHz in LTE-M or 200 kHz in NB-IoT), the PAs high gain mode (described in [11]) used in smartphones PAs might not be needed and hence can be removed. This means

that the transmit power range where the high-gain mode is not used have to be extended from a maximum of 10 dBm to 23 dBm ($Ptx_{max,\mathrm{dBm}} = 23\,\mathrm{dBm}$). Notice that $Ptx_{max,\mathrm{dBm}}$ should be considered a parameter in this energy evaluation methodology and can be set to another value. The corresponding efficiency at $Ptx_{max,\mathrm{dBm}}$ is scaled to be 40 %, such that this model matches the assumption used in [3] for the constant efficiency model. This means that both models have the same power consumption at $Ptx_{max,\mathrm{dBm}}$.

The resulting PA efficiency model proposed for MMTC devices, which has been derived from [11], is described in (4) and consists of two states; one where Ptx_{dBm} takes values from −30 dBm to 0 dBm where the power consumption is constant as in [11], and one where Ptx_{dBm} takes values from 0 dBm to 23 dBm where the power consumption increases at a moderate rate.

$$\begin{aligned} P_{TX}(Ptx_{\mathrm{dBm}}) &= P_{PA}(Ptx_{\mathrm{dBm}}) \\ &= \begin{cases} 0.0197 \cdot Ptx_{\mathrm{dBm}} + 0.0454, & \text{if } 0 < Ptx_{\mathrm{dBm}} \leq 23 \\ 0.0454, & \text{if } Ptx_{\mathrm{dBm}} \leq 0 \end{cases} \quad [\mathrm{W}] \end{aligned} \tag{4}$$

The radio PA efficiency model for MMTC is depicted in Fig. 4 along with the commonly used constant PA efficiency model. The power consumption is given in relative values (in log scale) to the power consumption at $Ptx_{max,\mathrm{dBm}}$.

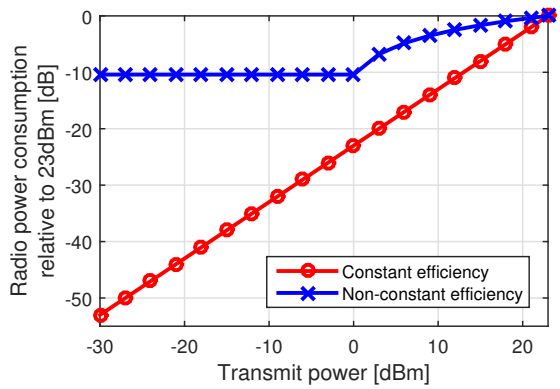

Fig. 4. Radio PA power consumption ($P_{PA}(Ptx_{\mathrm{dBm}})$) for the proposed (non-constant efficiency) model for MMTC radios vs. the commonly used constant efficiency model (40 %).

This new model will result in higher energy consumption if transmit powers lower than maximum transmit power ($Ptx \leq Ptx_{max}$) is used, as it models a lower efficiency than the constant model for $Ptx < Ptx_{max}$.

3 Results

This section demonstrates the use of the proposed energy evaluation methodology described in the previous section. Assumptions and parameters used throughout this section are listed in table 1.

Table 1. Assumptions and parameters

Channel model	
Path loss (PL)	154 dB
Shadow fading	Eliminated by power control
Bandwidth	1.08 MHz
Noise	Noise figure (2 dB), thermal noise (−111 dBm)
Performance curve	
Target performance	10 % error rate
$\gamma SINR$	Mode A (−18.9 dB), mode B (−11.0 dB)
Power model	
P_{TX}@23 dBm	500 mW
P_{other}	60 mW
T_{TX}	Mode A (0.903 ms), mode B (0.237 ms)
PSM	$P_{PSM} = 0.015$ mW, $T_{PSM} = 60$ min
$Idle$	$P_{Idle} = 3$ mW, $T_{Idle} = 2$ s
RX	$P_{RX} = 70$ mW, $T_{RX} = 0.36$ s
Power control	Uplink open loop with $\alpha = 1$
Traffic model	UL only. Poisson call inter-arrival
Deployment	Single cell. Path-loss compensated by PC
Access configuration	Transmission in all TTI. Consecutive repetitions.

The assumptions intend to model a MMTC device which on average spends 60 min in PSM state between consecutive uplink transmissions. Before it is ready to transmit its payload it has to perform synchronization and read the needed control channel. Then it initiates the transmissions and stays in TX state until all transmit repetitions have been performed. The values used in this evaluation are inspired by NB-IoT and should be considered as example values only. The power consumption values are from [7]. The time to conduct synchronization is from [5] and set to 200 ms which is spend in RX. The total acquisition time of the control channel is from [6] and is set to 2 s which is spend in $Idle$ and 160 ms in RX.

3.1 Impact of power control

To demonstrate the impact of uplink power control on the energy consumption, Fig. 5 shows the transmit power at different traffic intensities (M) with the number of transmit repetitions (R) ranging from 1 to 512. All devices are using the same number of transmit repetitions. The white area is the outage region and is clearly seen at the right and in the lower right corner. The outage region

is where (2) is not satisfied meaning that the power control requests a transmit power above the maximum allowed (Ptx_{max}) and the UL γ_{SINR} cannot be met.

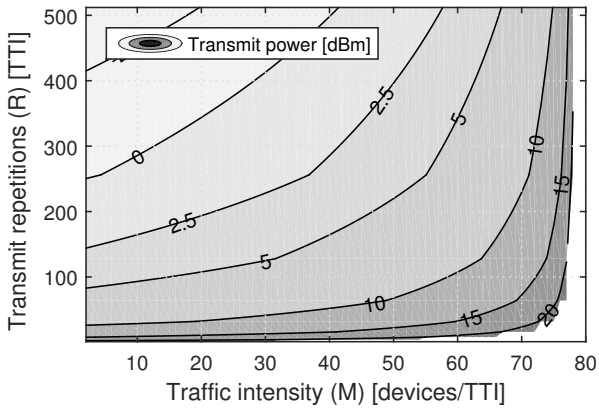

Fig. 5. Contour plot of the radio transmit power for performance curve A. It can be interpreted as if 50 devices are transmitting at the same time ($M = 50$) and 64 transmit repetitions are configured ($R = 64$), then each device needs 10 dBm transmit power to reach the performance target.

The corresponding energy consumption to the transmit powers shown in Fig. 5 is shown in Fig. 6. The markers in Fig. 6 indicate the energy consumption if the transmit power is fixed to $Ptx_{\mathrm{dBm}} = 10\,\mathrm{dBm}$ means that power control is not utilized. Let's say that the traffic intensity at a given time is $M = 50$ devices / timeslot (TTI) and that $R = 64$ transmit repetitions is used. Then the traffic intensity increases to $M = 65$. To keep the target performance (γ_{SINR}) in the case that power control is not utilized, meaning that the transmit power is fixed, the number of transmit repetitions have to be increased. The result is an increase in energy consumption. However, if power control is utilized, the transmit power can be increased with the result of maintaining the energy consumption instead and keeping the target performance. This is illustrated in the figure as the two arrows from $M = 50$ to $M = 65$, one with power control (blue) and one with fixed transmit power (red). Note that it is the combination of the power model with the non-constant PA efficiency model for MMTC radios and power control that causes the non-linear energy consumption contour lines and enables new options to optimize the device energy consumption.

3.2 Impact of performance curves

Two modes are considered (A and B) each having a performance curve (A and B in Fig. 2) and transmit time. The target performance error rate is the same (10 %), but the corresponding target SINR (γ_{SINR}) is different $-18.9\,\mathrm{dB}$ for

mode A and −11.0 dB for mode B (see also table 1). The time it takes to transmit a single transmission is set to 0.903 ms and 0.237 ms.

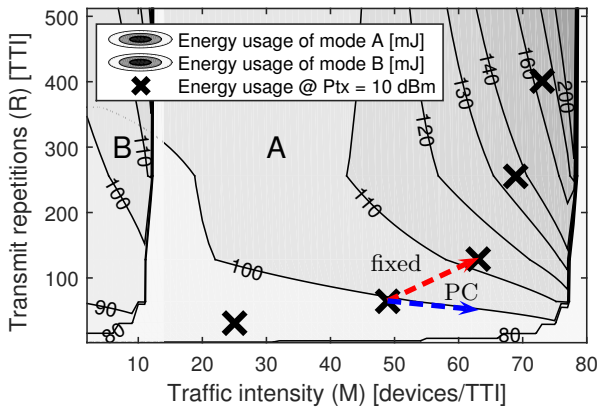

Fig. 6. Contour plots of the device energy consumption for mode A ($M = [14, 78]$) and B (for $M = [1, 12]$) with power control as a function of transmit repetitions and traffic intensity. The crosses in mode A are reference energy usage if the transmit power is fixed to 10 dBm. The arrows indicate the possible options when power control is used (blue) and not used (red) to keep the target performance when M increases from $M = 50$ with $R = 64$ to $M = 65$.

The energy consumption of mode A and B are seen in Fig. 6. Note the significant difference in the range of traffic intensity, which is much lower in B at $M = 12$ than in A at $M = 78$. The outage region appears much earlier with mode B due to the higher γ_{SINR} which is close to 10 dB higher. To compare the energy consumption of the two modes in further detail, one method is to extract energy consumption values at the same traffic intensities and transmit repetitions. If the transmit repetitions is fixed to $R = 128$ it can be found that the energy consumption of B is slightly lower than A but only for $M \leq 10$ (e.g. at $M = 5$ the difference is 94.3 mJ against 97.4 mJ).

3.3 Impact of power model

Figure 7 shows the effect of the radio power model with a non-constant PA efficiency on the energy consumption. The figure shows that the energy consumption ratios between the two models range from 1 to 2 and have an average of 1.15 across traffic intensity and transmit repetitions. This means that using the power model with a non-constant PA model intended for MMTC radios will estimate a overall higher power consumption. The exception to this is when $Ptx = Ptx_{max}$, as it was expected. This is where the ratio is 1.

It should be noted that the energy consumption difference between the PA efficiency models only comes from the difference in energy consumption in TX

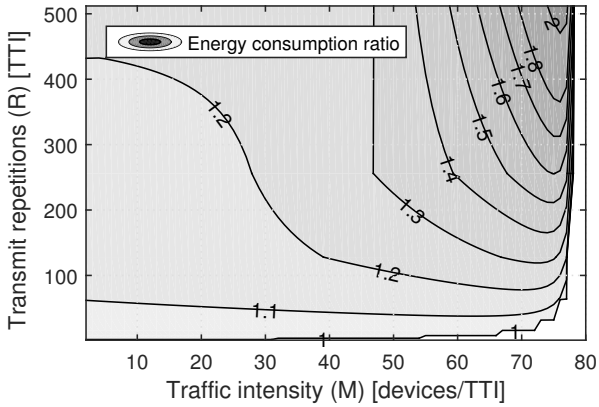

Fig. 7. Energy consumption ratio per transmission of the radio power model with the non-constant PA efficiency intended for MMTC devices over the commonly used radio power model with a constant PA efficiency model. Mode A is used.

state. But the energy consumption ratio depends on the energy consumption of the other states such as RX and $Idle$. For instance if the time spend in RX is increased to $T_{RX} = 1\,\mathrm{s}$ the average energy consumption ratio becomes 1.1 and the maximum ratio is 1.75. If T_{RX} is further increased to $T_{RX} = 2\,\mathrm{s}$ the average ratio is 1.07 and the maximum ratio becomes 1.5.

4 Discussion

The results shown in this paper demonstrate the generic energy evaluation methodology and emphasize the impact of uplink power control, link-level performance and the power model. This section will discuss the results and the implications of the methodology.

One of the assumptions is the path-loss which is set to 154 dB in the results. The reason for selecting the path-loss as one value is that shadow fading is omitted as it is assumed that the power control is capable of compensating for this. Path-loss selected as a single value can also be interpreted as an upper bound of the shadow fading. Introducing shadow fading as a random variable will correspond to introducing an imperfect power control, which is discussed later in this section.

The effect of using the non-constant PA efficiency model depends on the energy consumption of the transmit state compared to the other states (RX, $Idle$ and PSM) and the relative difference to the constant PA efficiency model. The relative difference of P_{TX} decreases as the transmit power increases (Fig. 4). However, when the transmit power increases the impact of P_{TX} in E_{tot} (3) increases. So when the transmit power increases on average, the average ratio

between the power models (Fig. 7) will also increase as long that $Ptx < Ptx_{max}$. The maximum ratio will however not change if $Ptx = Ptx_{max}$ is already present.

The power control used in the presented methodology is assumed to be perfect. This is defined here as if the devices are capable of doing perfect path-loss estimation and always have perfect knowledge of M and the path-loss. The effect of an imperfect power control will be that devices will select non-optimal transmit powers. Even if the average transmit power is the same as with a perfect transmit power, the average amount of devices which fulfils the target performance will decrease. The overall consequence is a lower outage capacity and a higher energy consumption, due to a higher transmit power and unnecessary retransmissions.

Throughout the paper it is assumed that all devices uses the same number of transmit repetitions. Translated into a cellular deployment it will correspond to a group of devices which uses the same configuration, but are orthogonal to other groups and devices in the cell. If the path-loss is not the same for all devices in the group, the power control really proves its worth as it allows the devices to regulate such that the received signal strengths after transmit repetitions at the BS receiver from the devices are still equally strong. When all devices in the group use the same number of transmit repetitions, the resource usage will also be fixed. This can, however, be optimized if devices are configured depending on their coverage conditions.

The proposed methodology is device centric and focus on the uplink transmissions. The example evaluation done in this paper is for one uplink transmission being transmitted with transmit repetitions. The example considers what happens when the device is sleeping, has synchronized, read the broadcast information and control channel, received downlink traffic, transmitted its uplink transmission and returned back to sleep. It is possible to use this methodology for a protocol consisting of multiple uplink and downlink transmissions. Downlink transmissions and their energy consumption impact are included as a parameter in the power model, where the most important parameter to change is how long time the device needs to be active. If the uplink transmissions utilize different modulation and coding scheme, multiple link-level performance curves will be needed.

The outcome of the proposed generic energy evaluation methodology is to make it easier to compare and evaluate standards and protocols for MMTC. The proposed methodology is simple, yet it includes important factors that affects the energy consumption. This means that evaluations done with this methodology are more realistic than those done with the existing energy evaluation methodology from [3]. Further the outcomes of this paper can and should be used as input when new MMTC protocols and standards are being developed.

5 Conclusion and outlook

This paper has presented a generic energy evaluation methodology tailored for MMTC. The methodology is demonstrated with special focus on three important

factors which affect the energy consumption evaluation; power control, link-level performance and radio power model. The results presented in this paper provide important take-away messages:

- Using the commonly used radio power model with a constant PA energy efficiency instead of the radio power model with a non-constant PA model intended for MMTC radios can result in an overestimation of the battery life up to 100 % and on average 15 % across traffic intensity and transmit repetitions configurations. The proposed PA efficiency model does, however, need to be validated using a similar approach as used in [11] when NB-IoT or LTE-M devices become available.
- The combination of link-level performance, power control and the radio power model with a PA model intended for MMTC devices, provides options to optimize both access capacity and energy consumption.

Future work involves applying the proposed methodology on concrete protocols and help the development of future cellular MMTC solutions. These could be for example, new schemes and protocols such as one-stage and two-stage access protocols by [14]. For simplicity, in the presented evaluation, all devices are assumed to use the same radio access configuration. This can be generalized and interpreted as a group of devices within a larger set of MMTC devices. Our future work will focus on how cell radio resource management and higher layer protocol mechanisms can help minimizing the device energy consumption when several groups of devices are considered.

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