An Empirical NB-IoT Power Consumption Model for Battery Lifetime Estimation

Mads Lauridsen[1], Rasmus Krigslund[1,2], Marek Rohr[3], Germán Madueno[3]
[1]Department of Electronic Systems, Aalborg University, [2]Kamstrup A/S [3]Keysight Technologies Denmark Aps
[1]Aalborg, Denmark, [2]Stilling, Denmark, [3]Aalborg, Denmark.
{ml, rkr}@es.aau.dk, {marek.rohr, german.madueno}@keysight.com

***Abstract*—The NB-IoT radio technology is a key enabler of the wireless Internet of Things. A competitive parameter is device battery lifetime, in addition to wide-area coverage and low device cost. In this paper, we present the first publicly available empirical power consumption measurements on two NB-IoT devices. The target is to provide a power consumption model for Internet of Things battery lifetime estimation.**

The commercially available NB-IoT device is measured to consume 716 mW when transmitting at 23 dBm, due to a power amplifier efficiency of 37 %. Receiving control and data channels require 213 mW, while the Idle-mode extended Discontinuous Reception and Power Save Mode sleep states consume 21 mW and 13 μW, respectively. In general, the power consumption levels are slightly higher than the 3GPP estimates, however the resulting estimated battery lifetime is promising, for this first generation device, being just 10 % shorter than the original 3GPP estimates.

I. Introduction

The Internet of Things (IoT) is predicted to experience massive yearly growth, in terms of number of devices today and the coming years [1]. A large share of the connected devices will utilize wireless communication for transferring sensor and actuator information. Many devices will be deployed in hard-to-access locations, making good wide-area coverage and long battery lifetime Key Performance Indicators (KPI), together with low device cost and a reasonable communication latency. To address these requirements, the 3rd Generation Partnership Project (3GPP) standardized the Narrowband IoT (NB-IoT) wireless communication technology in Summer 2016 [2], [3].

During the standardization phase, multiple 3GPP members proposed how current 4G Long Term Evolution (LTE) could evolve to fulfil the requirements, as evident from the multitude of technologies in [4]. A key requirement was 10 years battery lifetime for a predefined traffic profile. Therefore, each proposal was accompanied by an estimated device power consumption model. The proposed models include protocol analysis, i.e. time to establish the connection combined with statistics on synchronization and random access [4]. Thus, they are complicated to use and a simpler model, based on real measurements, is needed. However, until today there are no publicly available power consumption measurements on NB-IoT devices. This is critical for the further evolution and market penetration of NB-IoT, as developers, researchers, and mobile network operators do not have a clear view of what the technology can provide in terms of battery lifetime. Some chip vendors do provide confidential power consumption data, but are often limited to a few values; 2-3 depending on uplink (UL) transmit power, 1 for downlink (DL) reception, and 1 for each of the important sleep modes NB-IoT includes; Idle-mode extended Discontinuous Reception (I-eDRX) and Power Save Mode (PSM) [2]–[4]. This makes it difficult for the user, to accurately estimate the battery lifetime for his application's specific traffic profile. In addition, the NB-IoT standard has a multitude of parameters, related to time domain repetitions and the I-eDRX and PSM sleep modes. Therefore, it is non-trivial to estimate the overall power consumption using pen-and-paper calculations, and thus measurements are needed.

In previous work, regular mobile broadband LTE power consumption modeling has been addressed by many researchers, see [5] for a review, while only a few papers have provided estimates of how future IoT technologies may perform, e.g. [6]–[8]. The contribution of this work is thus, to the best of the authors knowledge, to *present the first publicly available power consumption measurements on two NB-IoT devices*. One device is commercially available, while the other is a pre-commercial prototype. In addition, we present a comprehensive NB-IoT power model, and estimate the battery lifetime.

In this paper the modelling and measurement methodologies are presented first, followed by NB-IoT power consumption measurement results, depending on transmit power level, UL and DL data rates, and the I-eDRX and PSM sleep modes. Next, we compare our observations with 3GPP estimates from [4], and present battery lifetime estimations for two applications. Finally, we provide our discussion and conclusion.

II. Modeling Methodologies

This section contains the proposed NB-IoT power consumption model, and the related battery lifetime model.

A. Power Consumption Model

The power consumption model is based on the methodology described in [5] and adapted to NB-IoT. The model is divided into three components; the UL and DL baseband processing units are functions of channel bandwidth and link data rate, while the UL radio frequency front end depends on the transmit power level. The DL radio frequency front end is not modelled, to depend on the receive power level, because measurements in [5] demonstrated a negligible impact on the overall power consumption. The active data transfer model is

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complemented with idle mode, I-eDRX and PSM sleep power levels, including timing for ramping up/down the transceiver.

B. Battery Lifetime Model

To estimate the battery lifetime we apply a traffic profile, resembling the behaviour of sensor devices, where data is transmitted periodically with a predefined interval, t_i. Establishing and maintaining a connection requires the exchange of multiple messages between the UE and eNB, [9]. By measuring the total power consumed in these phases, we can abstract from these transmissions. This enables a power model with four phases for modelling the periodic traffic pattern:

P1: UE wakes up and establishes a connection.
P2: Data is transmitted.
P3: UE disconnects and returns to sleep/idle.
P4: UE sleeps/idles until the next transmission period begins.

The lifetime $L\left(t_i\right)$, in hours, is then given by:

$$L\left(t_i\right) = \frac{C_{bat} \cdot SF_{bat}}{P_m(t_i) + P_{device}} \qquad \text{[h]} \qquad (1)$$

Where C_{bat} is the battery capacity [Wh], SF_{bat} is the battery safety factor [-] accounting for self-discharge, $P_m(t_i)$ is the average power consumption [W] of the modem, throughout the period (composed of the phases P1-P4), and P_{device} is the sensor circuitry average power consumption [W], i.e. all but the modem. The lifetime in days, $L_d(t_i)$, is obtained by scaling $L(t_i)$ by the number of hours per day, i.e. $L_d(t_i) = \frac{L_(t_i)}{24}$.

The average modem power consumption, $P_m(t_i)$, is:

$$P_m(t_i) = \frac{\overbrace{E_{conn}}^{P1} + \overbrace{P_{tx} \cdot t_{tx}}^{P2} + \overbrace{E_{disconn}}^{P3}}{t_i} \qquad (2)$$
$$+ \frac{\overbrace{P_{idle} \cdot (t_i - t_{tx} - t_{conn} - t_{disconn})}^{P4}}{t_i} \qquad \text{[W]}$$

Where E_{conn} and $E_{disconn}$ are the energy [J], and t_{conn} and $t_{disconn}$ the duration [s], of P1 and P3 respectively. These depend on the network load, especially the former, and network settings, but in the controlled environment of this work they are considered constant. P_{tx} is the average power [W] consumed during P2, having transmission time, t_{tx} [s]. Finally, P_{idle} is the power consumed in the idle period [W], between transmissions and depends thus on the applied sleep mode (I-eDRX or PSM). The transmission time, t_{tx} [s], depends on the number of bytes to be transmitted, D [byte], and the average data rate R [bit/s]:

$$t_{tx} = D \cdot 8/R \qquad \text{[s]} \qquad (3)$$

III. Measurement Methodology

To determine the power consumption of the device-under-test (DUT), it must be connected to a NB-IoT base station while the voltage level and current draw is measured. Our measurement setup is illustrated in Fig. 1. The DUT's antenna port is connected, through cables, to a Keysight UXM, which is a standard-compliant NB-IoT base station emulator, with

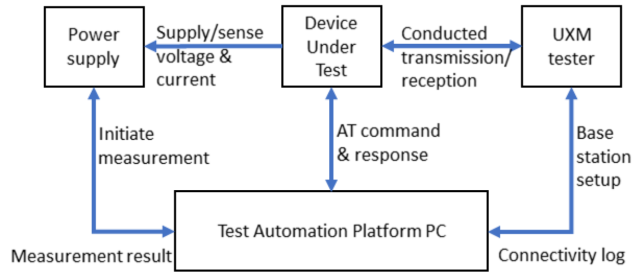

Fig. 1. Power consumption measurement setup.

debugging capabilities. The DUT's power consumption is supplied or sensed, depending on the device configuration, using a Keysight N6705C DC measurement supply. The measurement setup is controlled using Keysight's Test Automation Platform (TAP), which provides interfaces to both the measurement equipment, and is able to send AT commands to the DUT. The latter is used for controlling the DUT's initial NB-IoT connection setup, PSM capabilities, and reboots and resets of the DUT during tests. In addition, TAP is capable of synchronizing the protocol logs and power consumption measurements with ≤ 1 ms accuracy.

To characterize each component in the proposed power model, the DUT power consumption is evaluated using a number of test cases; transmit power, UL data rate, DL data rate, I-eDRX, and PSM. As the case names indicate, each test is focused on evaluating the impact of a specific radio parameter or feature. Therefore, in each test case all but one parameter, radio and network related, are fixed.

When the transmit power test case is executed, only the $p_{\max}$ parameter is varied. The reason is that $p_{\max}$ defines the DUT transmit power p_{Tx} for the Narrowband Physical Uplink Shared Channel (NPUSCH) as follows (when the number of repetitions is equal to one) [10]:

$$p_{\mathrm{Tx}} = \min\left(p_{\max}, \alpha \cdot PL + P_0 + 10\log_{10}(M)\right) \quad \text{[dBm]} \quad (4)$$

where α is the path loss compensation factor [-], PL is the downlink path loss estimate [dB], P_0 is the NPUSCH target level power [dBm], and M is a parameter depending on the subcarrier spacing Δf and the number of configured subcarriers [-], [10]. Note that the transmit power test case is performed using both the 3.75 kHz and 15 kHz subcarrier, that is $M = 1/4$ and $M = 1$, respectively. To ensure $p_{\max}$ always is the smallest term in (4), we apply full path loss compensation ($\alpha = 1$) and $P_0 = -60$ dBm.

To make sure the DUT is continuously transmitting during the measurement phase, the UXM enables the *fixed MAC padding* functionality. This prompts the DUT to fill the remainder of the currently allocated Transport Block with random data. Using this method it is possible to avoid sending AT commands, with application data, to the DUT, and thus minimize the control overhead impact on the power consumption.

The UL and DL data rate test cases also utilize the *fixed MAC padding* functionality. In order to evaluate the impact of varying UL data rates, i.e. different encoding complexities,

TABLE I

TEST CASES WITH UXM AND N6705C SETTINGS. I-EDRX PARAMETERS ARE IN NUMBER OF SUBFRAMES (SF) AND DEFINED AS IN [9].

Test case	UXM settings Varied parameter	Other settings	N6705C settings Sampling time	Max. current
Transmit power	$p_{\max} = \{-10:1:23\}$ dBm, $\Delta f = \{3.75, 15\}$ kHz	UL MCS= 4, $I_{\mathrm{RU}} = 6$, UL MAC padding NPUSCH Repetitions= 1	0.25 ms	3 A
UL data rate	UL MCS $= \{4, 7\}$, $I_{\mathrm{RU}} = \{0, 2, 4, 6\}$	$\Delta f = 15$ kHz, $=_0= -60$ dBm, $\alpha = 1$, UL MAC padding, NPUSCH Repetitions= 32	0.25 ms	3 A
DL data rate	DL MCS $= \{1, 4\}$, $I_{\mathrm{SF}} = \{0, 2, 4, 6\}$	$\Delta f = 15$ kHz, DL MAC padding	0.25 ms	3 A
I-eDRX	None	*longDRX-Cycle*= 1024 SF, *OnDurationTimer*= 4 SF, *StartOffset*= 0, *drx-InactivityTimer*= 8 SF, *drx-RetransmissionTimer*= 2 SF	1 ms	100 mA
PSM	None	T3324= 6 s, T3412= 20 hours	1 ms	1 mA

the Modulation and Coding Scheme (MCS) and the resource assignment field I_{RU} are varied. The combination of those parameters defines the Transport Block Size [10]. Similarly, the MCS and the DL resource assignment field I_{SF} are varied, when assessing the impact of the DL data rate [10].

When evaluating the impact of the I-eDRX and PSM sleep modes, data is not scheduled. The starting point, as in all other test cases, is to make the DUT Radio Resource Configuration (RRC) connected. In the case of PSM, the absence of scheduled data first triggers the DUT to be moved to RRC Idle mode, and then to a RRC null state, where it is still registered with the network [11]. For I-eDRX the inactive DUT will return to sleep mode after the *OnDurationTimer* has expired, [9].

Table I contains the detailed UXM settings for each test case. Furthermore, the sampling time and maximum current of the N6705C is specified. The maximum current is adjusted, to measure hundreds of milliampere, in the high transmit power case, and a few microampere, in the PSM sleep mode case. In each test case, the power consumption is measured for 10 s, before stepping to the next value of the parameter under test.

All measurements are made in LTE band 20 (~ 800 MHz) using a single, in-band, 15 kHz subcarrier, except for the transmit power test case, which also uses 3.75 kHz subcarrier spacing. In general, the Downlink Control Information subframe is repeated 8 times, while the UL and DL shared data channels use 32 repetitions [10].

IV. MEASUREMENT RESULTS

This section contains the measurement results of each test case in Table I. Device A is commercially available, however with a Q4 2017 firmware, while device B is a pre-commercial prototype. The performance of devices from both vendors is expected to improve significantly in 2018 and onwards due to ongoing firmware and power optimizations.

The power consumption as a function of the device UL transmit power is a KPI for NB-IoT devices. Devices in bad coverage conditions, will utilize multiple repetitions with maximum transmit power, to ensure the data is received by the base station, and thus high power amplifier efficiency (PAE) is important. Fig. 2 shows the measured power consumption when transmitting in either a 3.75 kHz or a 15 kHz subcarrier. As expected, the power consumption is independent of the

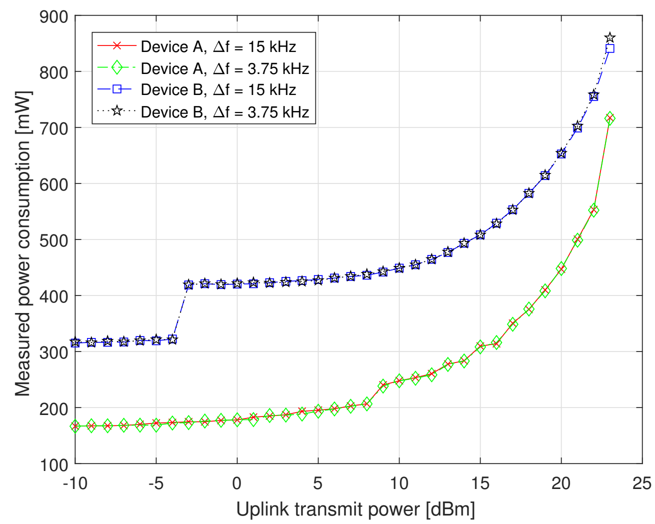

Fig. 2. Measured power consumption as a function of UL transmit power and subcarrier spacing (Δf).

subcarrier spacing. Assuming the base power consumption for device A and B is equal to the consumption at -10 dBm the PAE is $\sim$37 %, at 23 dBm, for both devices.

The total ON time of a NB-IoT device will in many cases define the overall battery lifetime. Therefore, it is of interest to study, the impact of UL and DL data rates on the power consumption, because a high data rate entails, the total ON time is reduced. Fig. 3 shows the measured power consumption as a function of UL and DL transport block size (TBS), which can be directly linked to the achievable data rate. In NB-IoT, the maximum TBS is 1000 bits and 680 bits for UL and DL, respectively [10]. As evident from Fig. 3 the power consumption is independent of both the UL and DL data rate for both devices. The power consumed during data reception, which also corresponds well to the synchronization phase and decoding control information, is about 210-240 mW. Note, the uplink data rate power consumption is defined by the maximum transmit power level in Fig. 2. The minor power consumption dependency on the UL and DL data rate is in line with previous observations on regular LTE, [5].

When the NB-IoT device is not actively communicating

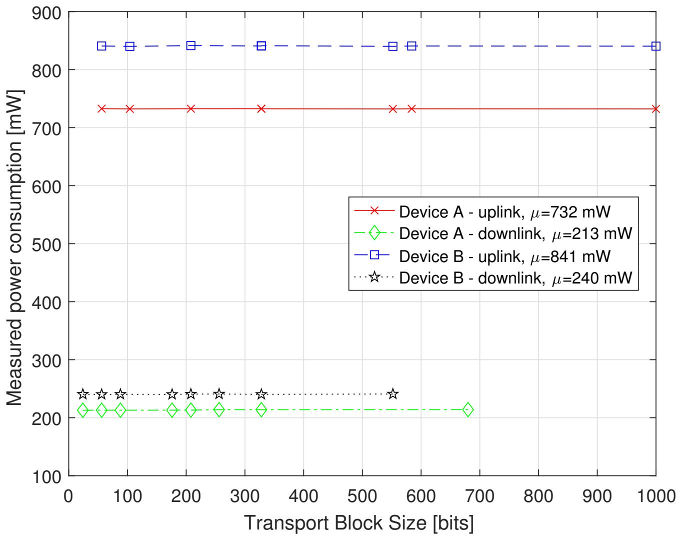

Fig. 3. Measured power consumption as a function of UL/DL data rates, by sweeping across the MCS indexes.

TABLE II
MEASURED POWER CONSUMPTION VERSUS 3GPP ESTIMATE FROM [4].

	Device A	Device B	3GPP [4]
Transmit†	716 mW	840 mW	480 mW
Receive	213 mW	240 mW	75 mW
Sleep‡	21 mW	23 mW	3 mW
Standby§	0.013 mW	0.035 mW	0.015 mW

† 23 dBm, ‡ I-eDRX for devices A & B, § PSM for devices A & B

with the serving base station, it may utilize either the I-eDRX or PSM sleep modes to conserve energy. The I-eDRX test case shows devices A and B consume 21 mW and 23 mW, respectively. The PSM test case results in 14 μW for device A and 35 μW for device B.

The measured power consumption results of the four test cases are summarized in Table II. The results are compared with the 3GPP estimates in Section VI.

V. BATTERY LIFETIME ESTIMATION

As defined in Section II-B the battery lifetime can be estimated by dividing a transmission into four separate phases. In addition to the active data transfer and idle phases (P2 and P4) it is important to understand the energy consumed during the attach and release phases (P1 and P3), as also specified in (2). The procedures are defined in [9], and they can be configured using a multitude of parameters.

Using the measured power values we apply (1) and (2) to estimate the lifetime for hourly and daily transmissions. In the idle period between transmissions (P4) the sleep modes I-eDRX and PSM, as well as power cycling of the module, are applied. The latter assumes the modem is powered OFF in between transmissions. The battery lifetime estimates are compared with the 3GPP reference [4], which was made before the NB-IoT standardization was completed. However, it is the only publicly available reference to NB-IoT-like device power consumption. Details on the estimated power consumption are available in Table II.

TABLE III
ASSUMPTIONS USED FOR LIFETIME ESTIMATES.

Payload size (D)	100 Bytes
Battery capacity (C_{bat})	27.7 Wh (C-cell)
Sensor average power consumption (P_{device})	0 W
Safety factor (SF_{bat})	1/3
Data rate (R)	300 bps
Transmit interval (t_i)	[1 h, 24 h]

TABLE IV
MEASURED P1 AND P3 ENERGY CONSUMPTION AND DURATION OF DEVICE A.

	I-eDRX	PSM	Power cycle
E_{conn}	3.2 J	3.5 J	11.1 J
$E_{disconn}$	0.57 J	0.58 J	0.54 J
t_{conn}	6.5 s	10.5 s	36 s
$t_{disconn}$	8.25 s	9.6 s	7.1 s

The lifetime estimates are based on the capacity of a C-cell battery [12], where we apply a safety factor of $SF_{bat} = 1/3$ to account for the self-discharge throughout the lifetime of the sensor. Since the focus of this work is on the modem power consumption, we assume an average power consumption of the sensor circuitry, $P_{device} = 0$ W. This means that all the available battery capacity is allocated to the modem. Each transmission, regardless of transmission interval, is 100 Bytes. The data rate is assumed to be 300 bps, which corresponds to the data rate achieved at the Maximum Coupling Loss (MCL) of 164 dB targeted by NB-IoT [13]. As evident from Fig. 3, the data rate does not directly impact the power consumption, but it has a major indirect impact, because it defines the overall device ON time. Table III summarizes the assumptions used for the battery lifetime estimates.

Moreover, [4] specifies the lifetime for NB-IoT to be approximately 10 years for $t_i = 24\,h$, a 5 Wh battery capacity, and a payload of 200 Bytes. In order to make a fair comparison with our measurement, the lifetime of this reference technology is estimated using the power levels from [4] and the energy and time measurements from Table IV.

Device B is a pre-commercial prototype and thus not relevant for lifetime estimation. Therefore, the power and duration of phases P1 and P3, listed in Table IV, have been measured using Device A, which is commercially available.

Table V lists the estimated lifetimes. When $t_i = 1\,h$ is applied, Device A achieves a lifetime of only 2.5 weeks. This is due to the relatively high power consumption during I-eDRX. When using power cycling or PSM the lifetime increases to 0.3 years and 0.6 years respectively. This is $5 - 10\,\%$ shorter than the 3GPP estimate for NB-IoT. Increasing t_i to $24\,h$, the lifetime of Device A increases significantly, up to 12.8 y in PSM. This lifetime resembles the 3GPP estimate, being just $6\,\%$ shorter. Note that PSM achieves far better lifetime than

TABLE V
ESTIMATED LIFETIME FOR A TRANSMIT INTERVAL $t_i = [1\,\text{h},\ 24\,\text{h}]$.

t_i	Technology	I-eDRX	PSM	Power cycle
1 h	3GPP [4]	88 d (0.2 y)	256 d (0.7 y)	108 d (0.3 y)
	Device A	17 d (0.0 y)	230 d (0.6 y)	103 d (0.3 y)
24 h	3GPP [4]	126 d (0.3 y)	4998 d (13.7 y)	2583 d (7.1 y)
	Device A	18 d (0.1 y)	4677 d (12.8 y)	2462 d (6.7 y)

power cycling the device. This is due to the expensive access procedure, in terms of energy, when booting the device.

VI. DISCUSSION

Using the test case measurements, a general model of the NB-IoT device power consumption can be established. In Table II, our measurement observations are compared with the 3GPP estimate [4], which was made before NB-IoT was fully standardized. The power consumption at high transmit power is significantly underestimated, partially because the 3GPP estimates use 45-50 % PAE, while the measurements show $\sim 37\,\%$. Similarly, the receiver's power consumption is 2-3 times higher than estimated, while I-eDRX sleep is even 7 times higher, albeit in line with current LTE [5]. The estimated standby consumption, i.e. PSM, for the commercial device A is accurate. Additionally, it should be noted that the power consumption in I-eDRX sleep mode of future NB-IoT modules is expected to resemble that of PSM mode, only differenced by the occasional paging window where the receiver is active.

As evident from Section V, the overall battery lifetime estimate is well above 10 years, even when considering a worst case scenario in terms of bandwidth. Our estimates are thus on par with the estimates from 3GPP. Moreover, we expect the device power consumption, in both active and sleep modes, improves with new firmware and hardware versions as was also observed during the first years of LTE, [5]. Moreover, features like Release Assist, which are defined in the NB-IoT standard, but yet to become a commodity in hardware implementations, are expected to optimize the power consumed during the release phase.

These initial NB-IoT measurements were made with focus on the instantaneous power consumption, as a function of transmit power, UL and DL data rates, and the I-eDRX and PSM sleep modes. However, the NB-IoT standard allows for many time domain adjustments, due to the use of repetitions in the control and data planes, [10]. Therefore, future work may focus on exploring the impact on battery lifetime, as a function of time domain settings. In addition, it is important to study the impact of network load, other PSM and I-eDRX settings, and the use of Control Plane CIoT EPS data transfer functionality, where user data is piggybacked in control messages [3].

VII. CONCLUSION

In this paper, we presented initial power consumption measurements on one of the first NB-IoT devices. The results show that uplink transmissions with 23 dBm require 716 mW. This is partially due to the power amplifier efficiency being about 10 %-points lower than 3GPP expected. The Discontinuous Reception power consumption is in the order of 21 mW, while the Power Save Mode is 13 μW. The latter is in line with 3GPP estimates, while the other measured values, of this first generation NB-IoT device, exceed the estimates.

Using our measurements, we assess the battery lifetime and compare with the numbers obtained during 3GPP standardization. The results are very promising, as we estimate the battery lifetime is only 5-10 % shorter than the estimates from 3GPP, when Power Save Mode is applied. As opposed to this, using Idle-mode extended Discontinuous Reception will result in a much shorter battery lifetime, due to the power consumption being multiple times higher than expected, in this first generation NB-IoT module. However, we expect the general power consumption performance to improve with future firmware and hardware versions.

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