Evaluation of Efficient Modes of Operation of GSM/GPRS Modules for M2M Communications

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Abstract—The field of machine-to-machine (M2M) communications has gained wide popularity and is steadily growing. This paper studies the feasibility of using the Global System for Mobile Communications and in particular the General Packet Radio Service (GPRS) for a low data rate long-lasting battery-powered operation of M2M devices. A model is introduced to estimate the power consumption of a GPRS connection. It allows the identification and evaluation of optimizations of the data transmission procedures. Two M2M modes of GPRS operation are introduced. For applications with frequent transmissions, an "Always-on-mode" turns out to be most reasonable. For infrequent transmissions, e.g., one transmission every 2 hours, an On/Off-mode reduces the power consumption of M2M devices by 93% as compared to the Always-on-mode. With a 3-cell battery providing 25.9 Wh of energy and considering only the power consumption of the communication module, a battery lifetime of up to 5 years is feasible. Measurements show that usually 40% of the energy spent for a short data transmission is wasted by one particular GPRS procedure called non-DRX period. Avoiding this saves up to 35% of total average power, depending on the rate of data transmissions.

I. INTRODUCTION

The field of machine-to-machine (M2M) communications is growing rapidly. With over 12.5 billion internet-connected devices today, we will have 25 billion devices in 2015 and about 50 billion devices in 2020 [1]. One key questions is how these devices can be connected efficiently. Cellular networks are seen to be one possibility because many devices operate far away from any wired connection. Moreover, they make the use of an additional intermediate gateway technology superfluous and thus help to reduce costs. The Global System for Mobile Communications (GSM) is deployed almost all over the world and, as mobile traffic shifts to more advanced technologies, operators are seeking for new revenue streams. This makes it a convenient candidate for M2M applications. However, GSM and its extension for packet-switched data transmission, the General Packet Radio Service (GPRS), are designed for phone calls, web browsing and streaming applications. The requirements of these applications, e.g., high data rates, often contradict with those of M2M applications, which often only require low data rates. Many M2M use cases do not become profitable until the devices can be operated for several years with a single battery.

The focus of the research results presented in this paper is on very small data messages, i.e., a few bytes, with moderate latency requirements. A possible application scenario is parking monitoring, which allows car drivers to quickly find a free spot in a parking lot.

We introduce a connection model which helps to estimate the minimum power consumption of an M2M data connection using GPRS. The model allows to identify procedures that have a great impact on the power consumption. Based on these results, optimizations of the data transmission procedures are proposed which can help to reduce power consumption of M2M devices operating in GSM-based cellular networks.

The procedures necessary for a GPRS data transmission as defined in [2]-[4] can be summarized as follows. The Mobile Station (MS), which is in our case an M2M device, first synchronizes with the base station of an appropriate cell and reads out its configuration. To register to the network, the MS performs the GPRS attach procedure, where it is identified and authenticated in the network. After that, the MS carries out a Packet Data Protocol (PDP) context activation procedure to establish a logical connection into a packet data network (PDN), e.g., the Internet. After registration, the MS is able to transfer user data over the air. The application that runs on the MS hands its data packets into the GPRS stack where they are processed and sent via a Temporary Block Flow (TBF), delivered through the network into the PDN, and finally routed to their destination. A TBF is a unidirectional flow of packets between the MS and the packet control unit (PCU) of the network. The duration of a connection is not predetermined. It can last from seconds to days or even weeks. When the connection is no longer needed, the MS deregisters with the PDP context deactivation and the GPRS detach procedure. During and between these procedures the MS...
performs several supporting procedures. For example, it has to stay synchronized in frequency and time, listen for paging blocks, and make cell measurements. Figure 1 illustrates all these steps and shall be the basis for the power consumption analysis in this paper.

Previous work on modeling the energy consumption of GSM data transmissions has been done for example in [5], [6]. However, to the best knowledge of the authors, no model which includes the overall power consumption including setup procedures and means to evaluate the long term energy consumption has been shown so far.

The rest of the paper is organized as follows. The next section introduces a model to estimate the power consumption of the previously described GPRS connection. The model is backed with measurement data and evaluated in III. In IV, two M2M modes of GPRS operation are introduced and compared using the model. An additional source for optimization, the non-discontinuous reception (non-DRX) period, is discussed in section V. Section VI provides estimates on the lifetime of battery powered M2M devices using the GPRS system with the optimizations discussed in this paper. Finally, conclusions are drawn in section VII.

II. CONNECTION MODEL

We introduce a model to estimate the power consumption of a GPRS connection as explained before. It is intended to identify what impact the different parts of the connection have on the device power consumption. This allows us to focus on improvements of GPRS procedures that draw the device battery the most. At the same time, it gives us a tool to estimate the potential savings that can be obtained by different improvements. Finally, it can be used to estimate the device lifetime using GPRS.

A. Model Description

The model consists of three parts as shown in Figure 2. First, a setup procedure is carried out to establish a data connection. Once a connection has been established, several data transmissions are performed. Between these data transmissions, the MS is in a keep alive phase to stay connected to the network. \( T_C \) denotes the total length of a connection.

The setup procedure comprises all parts which do not belong to the user data transmission but are necessary to properly connect to the network. This includes the initial cell selection as well as frequency, burst, and frame synchronization, acquisition of system information messages on the broadcast channel, GPRS attach/detach, and PDP context activation/deactivation. For carrying out one setup procedure, the device consumes an energy \( E_S \). The duration \( T_S \) of the setup procedure is considered to be small as compared to \( T_C \).

The actual user data transmission can be seen as the transfer of a small message from the MS to a server in a PDN. A user data message consists of a single User Datagram Protocol (UDP) packet with 5 bytes of user data. The MS can transfer many of these messages during a connection, where the rate is denoted by \( \lambda_D \). When considering a fixed rate, this can be understood as data transmissions with constant rate, i.e., one transmission every \( x \) time units, or as a mean value derived from some probability distribution. Each data transfer includes the transmission of one uplink TBF and a non-DRX period. The energy spent for the transfer of one single message is denoted by \( E_D \).

Between data transmissions, several procedures must be executed to maintain a proper connection to the network. The keep alive phase comprises these procedures and consists of listening for paging as well as frequency, burst, and frame resynchronization, and neighbor cell measurements. The average power consumption during keep alive phase is denoted by \( P_K \).

B. Total Power Consumption

We now derive the total average power consumption \( \bar{P} \) of a connection. Each considered part contributes a certain amount of average power consumption to \( \bar{P} \). These contributions are denoted by \( \bar{P}_S \) for the setup procedure, \( \bar{P}_D \) for the user data transmissions and \( \bar{P}_K \) for the keep alive phase. The total average power consumption follows as

\[
\bar{P} = \bar{P}_S + \bar{P}_D + \bar{P}_K.
\]

The setup procedure requires an energy \( E_S \), as mentioned before. The average power consumption of the setup is \( \bar{P}_S = \frac{E_S}{T_C} \), which relates the energy that is spent for the setup to the overall connection time \( T_C \), rather than to the setup time \( T_S \). In our use case scenario, the battery-driven M2M devices shall be in place for several years. Thus, the goal is to keep the connection alive as long as possible. Therefore, we assume a very long connection \( (T_C \to \infty) \), which leads to

\[
\bar{P}_S = \frac{E_S}{T_C} \lim_{T_C \to \infty} 0.
\]

As the energy required for one data transmission has been defined as \( E_D \) and this procedure occurs with a rate \( \lambda_D \), the average power consumption of all data transmissions is

\[
\bar{P}_D = \lambda_D E_D.
\]

As defined in the previous section, the average power consumption during the keep alive phase is denoted as \( \bar{P}_K \). In contrast, we denote the average power consumption of the keep alive phase over the total connection length as \( \bar{P}_K \). Thus, to obtain \( \bar{P}_K \), \( \bar{P}_K \) must be scaled down by the ratio \( \frac{t_K}{T_C} \), where \( T_K = T_C - n_D T_D - T_S \) is the total time the device is in the keep alive phase. The total time the device is in data transmission phase is \( n_D T_D \) with \( n_D = \lambda_D T_C \) being the total number of

![Fig. 2: Connection model](image-url)
data transmissions. For the same reason as above, we assume a very long connection length \( T_C \rightarrow \infty \). Practical values for the setup length \( T_S \) are several seconds. Thus, the scaling factor becomes

\[
\frac{T_K}{T_C} = \frac{T_C - \lambda_D T_C T_D + T_S}{T_C} \approx (1 - \lambda_D T_D) . \quad (4)
\]

Now we can state the average power consumption of the keep alive phase as

\[
P_K = (1 - \lambda_D T_D) \bar{P}_K . \quad (5)
\]

The total average power consumption \( \bar{P} \) of a connection can now be written as

\[
\bar{P} = \bar{P}_D + P_K = \lambda_D E_D + (1 - \lambda_D T_D) \bar{P}_K . \quad (6)
\]

### III. Modelling Results

To further work with the previously derived model we have determined the values of the used parameters by measurements on a SIM900 GPRS module [7]. The module is a GPRS class B device with power class 1 (1 W max. output power) configured in multi-slot class 8 and operated in PCS band (1900 MHz). During the measurements the module has indicated a receive signal strength of \(-96\) dBm. Unfortunately, the module does not provide any means to determine the output power level. The power consumption during transmission of the bursts has been measured to be approximately 5 W. Under the assumption that the device operates at its maximum output power level of 1 W, we can conclude that the values discussed in the text.

Using these values and the previously derived model (6), it is possible to approximate the power consumption of a connection. Figure 3 shows this average power consumption \( \bar{P} \) and how both phases, the data transmission phase with power consumption \( \bar{P}_D \), and the keep alive phase with power consumption \( \bar{P}_K \), contribute to the total amount. The power consumptions are plotted over \( 1/\lambda_D \), which is the average time interval between two consecutive data transmissions. The power consumption during transmission of the bursts has been measured to be approximately 5 W. Under the assumption that the device operates at its maximum output power level of 1 W, we can conclude that the values discussed in the text.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E_D )</td>
<td>Energy required for a data transmission</td>
<td>0.47</td>
<td>Ws</td>
</tr>
<tr>
<td>( E_{D, On/Off} )</td>
<td>Energy required for data transfer in On/Off mode</td>
<td>0.28</td>
<td>Ws</td>
</tr>
<tr>
<td>( E_{nonDRX} )</td>
<td>Energy required for non-DRX period</td>
<td>0.19</td>
<td>Ws</td>
</tr>
<tr>
<td>( E_S )</td>
<td>Energy required for setup procedure</td>
<td>3.9</td>
<td>Ws</td>
</tr>
<tr>
<td>( T_{nonDRX} )</td>
<td>Duration of the non-DRX period</td>
<td>2</td>
<td>s</td>
</tr>
<tr>
<td>( T_D )</td>
<td>Time for a data transmission</td>
<td>2.9</td>
<td>s</td>
</tr>
<tr>
<td>( \bar{P}_K )</td>
<td>Average power consumption during keep alive</td>
<td>8.5</td>
<td>mW</td>
</tr>
</tbody>
</table>

(\( E_{SP,PA,MFRMS = 4} \))

Additional parameters are explained later in the text.

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Now we can state the average power consumption of the keep alive phase as \( \bar{P}_K = (1 - \lambda_D T_D) \bar{P}_K \).

The total average power consumption \( \bar{P} \) of a connection can now be written as

\[
\bar{P} = \bar{P}_D + \bar{P}_K = \lambda_D E_D + (1 - \lambda_D T_D) \bar{P}_K \geq 5 \text{ W} . \quad (6)
\]

Increasing the intervals between transmissions. The reason for the drop of \( \bar{P}_K \) for small intervals is that \( 1/\lambda_D \) approaches the length \( T_D \) which results in a shorter time the module is in keep alive phase.

For intervals smaller than 17 s, \( \bar{P}_D \) dominates the total power \( \bar{P} \) with over 80%. In contrast, for intervals larger than 3.8 min, the consumption \( \bar{P}_K \) of the keep alive phase contributes over 80% to the total power consumption.

Knowledge about how the different phases influence the total power consumption will now help us to look for optimizations on the procedures that influence the power consumption the most for a specific use case. For infrequent data transmissions, the keep alive phase dominates the power consumption. The next section shows an approach for reducing the power consumption in those cases.

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### IV. Two M2M Modes of Operation

We introduce a new operational mode for GPRS-based M2M devices, the On/off-mode, which helps to significantly reduce the power consumption for use cases with large intervals between transmissions, if the use case does not require the MS to be reachable for incoming connections all the time. For the benefit of clarity, we denote the operation mode considered so far as Always-on-mode.

In the Always-on-mode the MS maintains a connection to the network all the time. This has two advantages. First, the MS is always reachable, e.g., for incoming data transfer or for maintenance. Second, the overhead of procedures that do not belong to the actual user data transmission is relatively low. A disadvantage of the Always-on-mode is that, no matter how large the time between transmissions becomes, the total power consumption stays always above the average power consumption during the keep alive phase, which is in our case \( \bar{P}_K \geq 8.5 \text{ mW} \). To overcome this issue, instead of maintaining the connection all the time, the MS can always establish a new connection to the network (initial synchronization, GPRS attach, PDP context activation), then perform the data transmission, and finally disconnect from the network (PDP context activation).
deactivation, GPRS detach). This process can be repeated for each data message, and shall be referred to as On/off-mode.

We model this behavior as shown in Figure 4. The setup procedure is modeled in the same way as described in section II. Since it does already include the procedures of establishing and releasing a connection, it is only present in the model before the data transmission. This simplification is adequate in our case because we are not interested in the power consumption as a function over time but only in its average value. We assume that in the periods between the user data transmissions, the module can be switched off completely such that it does not consume any power. Both, the setup energy $E_S$ and the energy $E_D$ required for a data transmission are consumed with rate $\lambda_D$. Thus, the power consumption of the setup procedures is

$$P_S = \lambda_D E_S.$$  \hspace{1cm} (7)

The energy spent for a data transmission changes in the On/off-mode. After the transfer of user data via the TBF, the MS begins immediately with the deregistration procedure and shuts off afterwards. Thus, there is no non-DRX period. The energy spent for this kind of data transmission shall be denoted by $E_{D,On/off}$. The resulting power consumption of the data transmissions is

$$P_D = \lambda_D E_{D,On/off}.$$  \hspace{1cm} (8)

Since the power consumption of the keep alive phase is $P_K = 0$, we can state the total average power consumption of a connection using the On/off-mode as

$$P_{On/off} = P_S + P_D = \lambda_D (E_S + E_{D,On/off}).$$  \hspace{1cm} (9)

Note that in the following the index ‘On’ indicates the Always-on-mode whereas ‘On/off’ refers to the On/off-mode. Table I shows the measured values of $E_S$ and $E_{D,On/off}$.

The value $P_{On/off}$ is the total power consumption of the connection averaged over time. Thus $P_{On/off}$ decreases linearly along with $\lambda_D$, whereas $P_{On}$ approaches $P_K$ when $\lambda_D$ decreases. Consequently, there must be a threshold value $\lambda_T$ at which the On/off-mode is more energy efficient than the Always-on-mode. This is the case when $P_{On/off} < P_{On}$.

Combining (6) and (9), $\lambda_T$ follows as:

$$\lambda_T = \frac{P_K'}{E_S + E_{D,On/off} - E_{D,On} + P_K'T_D} > \lambda_D.$$  \hspace{1cm} (10)

For the measured values, the threshold is $\lambda_T = 0.0023 \text{s}^{-1}$, which is equivalent to a transmission interval of $1/\lambda_T = 7.3 \text{ min}$. Figure 5 compares the total average power consumption of both considered modes over a wide range of transmission intervals $1/\lambda_D$. As predicted, the power consumption of the On/off-mode $P_{On/off}$ drops below the power consumption of the Always-on-mode $P_{On}$ for intervals bigger than the threshold $1/\lambda_T = 7.3 \text{ min}$. The optimal mode depends on the interval between user data transmissions. If the wrong mode is chosen for a particular rate $\lambda_D$, the power consumption is significantly higher than needed. If, for example, the transmission interval is two hours, the average power consumption is $P_{On/off} = 0.58 \text{ mW}$ when using the On/off-mode and $P_{On/off} = 8.5 \text{ mW}$ when using the Always-on-mode. Hence, the On/off-mode reduces the power consumption by 93% in this particular case. Even if the transmission interval $1/\lambda_D$ deviates only very little from $1/\lambda_T = 7.3 \text{ min}$, the potential savings are significant. For transmission intervals of 5 and 10 min the optimization potential is over 25%. Thus, it is essential to choose the correct mode even if the actual value of $\lambda_D$ is not far apart from the threshold value.

If the use case has a varying rate of data transmissions, such that the rate crosses the threshold value during operation, it appears reasonable to use a dynamic mode switching. This is possible, e.g., if the transmission rate follows a deterministic pattern. If the rate follows a certain probability distribution, the mean value of the rate could be used to choose the correct mode. This mean value could vary over time, or in some cases the transmission rate might depend on the state of the application. In those cases, the mode should be updated appropriately each time the expected rate crosses the threshold.

One advantage of this optimization is that it can be easily set by an application that controls the GPRS module of the M2M device. Furthermore, an isolation circuit is required which disconnects the module from the power source to minimize leakage and to reduce the power consumption between data transmissions to about zero. Note however, that there are no modifications of the GPRS standard required.

V. OPTIMIZATION OF THE NON-DRX PERIOD

When there is no data transmission, the MS is in a low-power state, which we call keep alive phase in our model. During this phase, the MS only switches on its radio to

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Fig. 4: On/off-mode of operation

Fig. 5: Power consumption M2M modes
decode the paging blocks of its paging subchannel. This is called discontinuous reception (DRX) mode. A disadvantage is, however, that the MS is only reachable during the paging blocks. This increases the delay for the establishment of incoming connections. Originally the GPRS system has been designed for web applications. Since the mentioned delay can have a negative effect on the user experience, a mechanism called non-DRX mode has been introduced in the GSM/GPRS standards, which works as follows. Suppose that the MS switches directly into DRX mode after a request for a web page has been sent. The network would have to wait for the next paging block of this MS to indicate that the server has answered. To avoid this delay, after each data transmission, the MS stays in non-DRX mode for a certain time $T_{\text{nonDRX}}$ before it switches to DRX mode. In non-DRX mode, the MS monitors the whole Common Control Channel (CCCH) for occurrences of immediate channel assignment messages and thus, it can avoid the delay for incoming connection establishment. The length $T_{\text{nonDRX}}$ of the non-DRX period is set by the non-DRX timer. Further details can be found in [4].

Figure 6 shows the measured power consumption over time of a data transmission with non-DRX period. Note that figure 6 has been optimized to show the non-DRX period, i.e., the power consumption is clipped over $0.6\,\text{W}$. In our case, the non-DRX timer value is $T_{\text{nonDRX}} = 2\,\text{s}$. The energy required by the non-DRX period is $E_{\text{nonDRX}} = 0.19\,\text{Ws}$, which is about $40\%$ of $E_D$.

For web applications or browsing, the non-DRX mode is an important feature to improve the user experience. However, for a use case which is not latency constrained, it is not needed. As we have seen, the non-DRX period consumes a major part of the energy of a data transmission. Therefore, it is reasonable to avoid this feature for M2M devices. To our benefit, the non-DRX timer value is negotiable during the GPRS attach procedure. It is contained in the DRX parameter information element in the attach request message sent by the MS (see [3] for message definitions). Thus, the MS can choose this parameter, and it should be possible to deactivate this feature. However, to the best knowledge of the authors, for modules currently on the market it is not possible to set this parameter by the application running on the device. Since the non-DRX timer has such a major impact on the energy consumption, it is advantageous to provide a possibility to control this parameter. One possible approach would be to define an additional AT command within the set of commands that are used to control the GPRS module. Figure 7 compares the optimized power consumption $P_{\text{On, opt}}$ (without non-DRX period) to the power consumptions we have seen so far. For $1/\lambda_D = 5\,\text{s}$, $35\%$ savings can be achieved. For $1/\lambda_D = 2\,\text{min}$, the power consumption can still be reduced by $12\%$.

VI. DEVICE LIFETIME

Based on the results, we shall now estimate how long a module can operate when powered on battery. For this, we consider only the power consumption of the GPRS module and neglect any self-discharge and the discharge curve of the battery. We assume the battery has a capacity of $Q_B = 7200\,\text{mAh}$ at a voltage of $V_B = 3.6\,\text{V}$. Thus, the battery provides an energy amount $E_B = Q_BV_B = 25.9\,\text{Wh}$. This is a typical 3-cell battery used in current traffic monitoring applications by Sensys Networks, Inc. [8]. The device lifetime can now be estimated as $T_B = E_B/P$, where $P$ is the average power consumption of the GPRS module. For $1/\lambda_D = 5\,\text{s}$, the battery lasts 17 days when using the Always-on-mode without the non-DRX period. It lasts only 11 days with the non-DRX period. For less frequent transmissions, e.g., $1/\lambda_D = 2\,\text{h}$, the battery lasts 1860 days (5.1 years) when using the On/off-mode, which becomes optimal in this case, whereas it lasts only 126 days when using the Always-on-mode.

VII. CONCLUSIONS

Using GPRS for low data rate M2M communications with battery-powered devices seems to be a promising approach. Based on the different steps of a data transmission, a model has been developed to estimate the power consumption of M2M devices using GPRS. The focus has been on applications with
small data messages (UDP packet, 5 byte user data) that do not require an answer from the receiving entity and have loose latency constraints of several seconds. The model provides the means to optimize procedures that affect the total power consumption the most, and it is a tool that can be used to estimate the device power consumption. Two M2M modes of GPRS operation have been considered, the *Always-on-mode*, which maintains a connection all the time, and a novel *On/off-mode*, which only connects the device to the network when a data message has to be transferred. The latter can significantly reduce the power consumption for very low data transmission rates $\lambda_D$. For example, for one transmission every 2 hours, the total average power consumption is only 7% as compared to the case when the *Always-on-mode* is used. It is of utmost importance to choose the correct mode for a specific value of $\lambda_D$, based on a threshold value $\lambda_T$. A drawback of the *On/off-mode* is that the MS will not be reachable for incoming requests, which is, however, not an issue for typical M2M applications. Furthermore, it has been shown that the non-DRX period consumes 40% of the total energy required for a data transmission. By avoiding it, savings of up to 35% in average power consumption can be achieved, depending on the data transmission rate $\lambda_D$. With a commonly used battery size of 25.9 Wh and one transmission every 2 hours, a device lifetime of about 5 years is feasible. These results make the GPRS system a promising candidate for M2M applications, which only require very low data rates and are not constrained in latency. Even though the introduction of an *On/off-mode* can reduce the power consumption significantly, still 90% of the power consumption is wasted by the setup procedure. This might be a topic for further research in this area.

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