Efficient Power Supply for Telemetry Sensor Nodes

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***Abstract*— Unidirectional telemetry systems for long range wireless data transmission are becoming more and more important for localization and sensor applications. A small size of the transmitter nodes, required for mobility, can only be reached by the use of tiny batteries. This paper explains, how an energy storage device like a capacitor can help to handle the current limitation of such batteries, e.g. coin cell batteries. Different circuits for the charge of the capacitor and for the power supply of sensor nodes are discussed. The efficiencies of the supply concepts are calculated and compared. The realizable number of transmissions for the different power concepts and a given type of battery is estimated. As a consequence of our calculations the optimal power concept could be implemented into our 1 cm^3 cubic transmitter demonstrator, which is introduced in this paper.**

***Index Terms*— telemetry systems, efficiency, energy storage, telegram splitting, coin cell battery, DCDC converter, LDO**

I. Introduction

Wireless long range telemetry is already established in metering applications, but is also gaining ground in systems for localization and transportation. The functionality of these networks is based on a huge number of transmitter nodes (TX), which communicate unidirectionally to a single receiver unit (RX) along standards like IEEE 802.15.4 [1]. A high efficiency of the TX node is essential for a long time of operation and enables the use of small batteries, e.g. coin cell batteries. Integrated Circuits (IC) for wireless communication, so-called System on Chip (SoC), typically requires several mA (e.g. $33\,\mathrm{mA}$ [7]) to reach an output level of $+10\,\mathrm{dBm}$ for a transmission at $868\,\mathrm{MHz}$. However, coin cell batteries have small capacity and their maximum output current is limited to few µA (e.g. 43 µA [10]). To close this gap, a buffering device like a capacitor C is required. This capacitor delivers the required energy during transmissions and is recharged from the battery between transmission cycles. Unfortunately, the periodic charge and discharge of C consumes energy. Several concepts for charging this capacitor and for the power supply circuit of the SoC will be discussed in this paper. The focus will be on the efficiency of the different concepts. Additionally, a range calculation for the realizable distance between TX and RX is made, as well as an approximation of the number of realizable transmission cycles by a coin cell powered TX node.

This paper is organized as follows: Section II describes the different concepts for the power supply of a sensor node. In section III the achievable number of transmission cycles is calculated. In section IV the hardware demonstrator of our miniaturized sensor node is presented. Finally, section V concludes the paper.

II. Power Supply Concepts of a Sensor Node

Semiconductors for wireless communication in the frequency range below $1\,\mathrm{GHz}$ typically require several mA for reaching an output level of approx. $+10\,\mathrm{dBm}$. Miniaturized batteries, so-called coin cell or button cell batteries, can often deliver only few µA of continuous current. An additional buffer capacitor C between the energy source and sink can solve this current mismatch for short periods. C is charged in the interval between two transmissions. During the active period of the TX, it is discharged with constant current. The amount of energy which can be drained out of the capacitor can be calculated along [4]:

$$E_C = \frac{1}{2}C(U_U^2 - U_L^2), \tag{1}$$

where U_U is the voltage at the start and U_L is the voltage at the end of a discharge period. C is assumed to be ideal without any equivalent series resistance (ESR). Some additional circuits are needed for the charge and the discharge of the capacitor. Fig.1. illustrates the different supply concepts. The red dashed line surrounds the devices required for charging the C and the blue dot-dashed line the power supply components of the SoC. For the efficiency calculation both parts are treated independently, i.e. C is not charged during the discharge period and reverse.

A. Charge Circuit

Using concept A (Fig.1.), C is charged by the battery via a resistor R to the level of the battery voltage U_B. The resistor R limits the maximum charge current to the

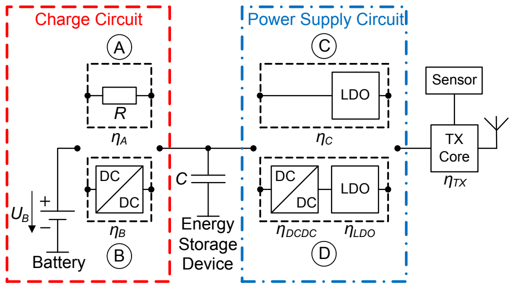

Fig. 1. Supply Concepts for a Transmitter node:
Concept A: Charge of C via a resistor
Concept B: DCDC converter with input current limitation
Concept C: LDO for powering the sensor node
Concept D: DCDC converter followed by a LDO

highest specified current which can be drained by the battery. The resulting efficiency η_A calculated as:

$$\eta_A = \frac{E_C}{E_C + E_R} = \frac{1}{2} + \frac{U_L}{2 \cdot U_U}, \tag{2}$$

where E_R denotes the energy dissipated by the resistor. The efficiency only depends on the voltage deviation of the capacitor *C*. The voltage drop caused by the transmission becomes smaller with increasing capacitor size. The value of the resistor itself has no influence on the efficiency, but on the time which is required for charging C.

In concept B, a step-down switching converter (DCDC) is used to charge the *C*, its input current must be limited. The efficiency for the charging process then equals the efficiency of the converter, where modern DCDC converters can achieve efficiencies in the order of $80\,\%$ to $95\,\%$ [9].

B. Power Supply Circuit

If concept C is used (Fig.1), a low drop-out regulator (LDO) accommodates the input voltage to a lower output level. The difference between output and input power is transformed into heat [6]. Today, a LDO is often integrated on SoC [7] to ensure the required quality of the power supply due to its filtering behavior. If the input voltage of the LDO drops linearly, its efficiency can be calculated along:

$$\eta_C = \frac{U_{LDO} \cdot I_{LDO}}{\frac{1}{2}\left(U_U + U_L\right) \cdot \left(I_{LDO} + I_q\right)}, \tag{3}$$

where U_{LDO} is the output voltage of the LDO and I_{LDO} is the constant current during discharge. The current I_q consumed by the LDO itself can usually be neglected [8]. The maximal duration of a transmission cycle is limited by the realizable $\Delta U_{in} = U_U - U_L$. The lower bound for U_L is the minimum required input voltage of the LDO. It is limited by the so-called drop-out voltage U_{DO}, compared to which value the input voltage must be higher than the required output voltage (e.g. $120\,\mathrm{mV}$ at $200\,\mathrm{mA}$ [8]).

If a DCDC converter is used ahead the LDO as in concept D, the energy from C can be converted down to the minimum required input level of the LDO with the high efficiency of the switching converter η_{DCDC}. The falling input voltage during the discharge is compensated by a higher drained input current. In this case the efficiency of the LDO η_{LDO} is at the highest realizable value and can be calculated along:

$$\eta_{LDO} = \frac{U_{LDO} \cdot I_{LDO}}{\left(U_{DO} + U_{LDO}\right) \cdot \left(I_{LDO} + I_q\right)}. \tag{4}$$

The efficiency of concept D is calculated as:

$$\eta_D = \eta_{DCDC} \cdot \eta_{LDO}. \tag{5}$$

C. Total efficiency

Combining the efficiencies of the power supply and the charge circuit, it is now possible to calculate the total efficiency of the TX node. If no DCDC converters are used, the efficiency follows:

$$\eta_{A,C} = \eta_A \cdot \eta_C = \frac{U_{LDO}}{U_U}. \tag{6}$$

This formula demonstrates that efficiency for this case is always constant and does not vary with the output energy. It is just depending on the ratio of the output voltage U_{LDO} and the peak voltage of the capacitor U_U, which equals the battery voltage U_B. When both DCDC converters are enabled the efficiency is calculated along:

$$\eta_{B,D} = \eta_B \cdot \eta_D = \eta_B \cdot \eta_{DCDC} \cdot \eta_{LDO}, \tag{7}$$

where η_B and η_{DCDC} are the efficiencies of the DCDC converters for the charge and discharge. The cases with a single DCDC for charge or discharge can easily be calculated along $\eta_{A,D} = \eta_A \cdot \eta_D$ and $\eta_{B,C} = \eta_B \cdot \eta_C$.

III. Number of Transmissions

A theoretical lower bound of the energy on the receiver side for decoding a packet of k bits with a specified error probability is given by Shannon's sphere-packing bound [5]. The energy E_{TX} for a packet of k bits required from the power supply can be calculated (cf. [4]) as:

$$E_{TX} = \frac{1}{\eta_{TX}} k F T_0 k_B L_P \left(\frac{E_b}{N_0}\right)_{RX}, \tag{8}$$

where F is the noise factor, $T_0 = 290\,\mathrm{K}$ denotes the standard temperature, k_B is the Boltzmann constant, E_b is the energy per bit, and N_0 is the noise floor. Furthermore, η_{TX} denotes the efficiency of the TX and is between $10\,\%$ to $20\,\%$ [7]. L_P represents the path loss and is realistically approximated along Okumura-Hata model [2], [3]. It calculates the path loss for urban environments without any antenna gain.

A modern telemetry receiver can realize a sensitivity of down to $-140\,\mathrm{dBm}$ [4]. This leads to a link budget of $150\,\mathrm{dB}$ in case of a transmission power of $+10\,\mathrm{dBm}$, if we furthermore assume an antenna gain of $0\,\mathrm{dBi}$ at the TX and RX side. The attenuation along Okumura-Hata reaches $150\,\mathrm{dB}$ at a distance of approx. $5\,\mathrm{km}$ with a correction factor for small / medium city environment and a height of $30\,\mathrm{m}$ above ground for the receiving antenna.

The maximum time for one transmission is limited by E_C. If this duration is not sufficient for reaching the required energy on the receiver side, a transmission telegram can be split up into several sub-packets. This mechanism is called telegram splitting [4]. The efficiencies calculated in the previous chapter are depending from the required output energy. When the data is split up to several sub transmissions, the C is charged and discharged several times, which affects the over-all efficiency.

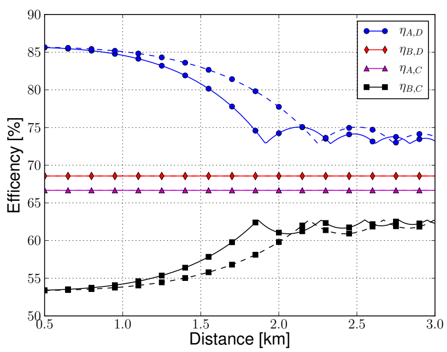

Fig. 2. Efficiencies of the different power concepts with $\eta_B = 0.8$, $\eta_{DCDC} = 0.9$, number of bits $k = 100$, $F = 10$, $(E_b/N_0)_{RX} = 1.5$, $\eta_{TX} = 0.15$, $U_U = 3.0\,\mathrm{V}$, $U_L = 2.1\,\mathrm{V}$, $U_{LDO} = 2.0\,\mathrm{V}$ and L along Okumura-Hata model. The size of the capacitor C is $680\,\mu$F for the continuous lines and $1200\,\mu$F for the dash lines.

Fig. 2. shows the efficiencies of the four power concepts in dependency of E_{TX} for typical parameters. For charge concept A with power supply concept C, referred to as (A,C), a constant efficiency of about 0.66 is reached, caused by the ratio $\frac{U_{LDO}}{U_U}$. In case (A,D), the best efficiency can be reached for short transmissions. A longer transmit cycle, equal to a higher voltage drop of the capacity voltage, leads to a reduced efficiency caused by the reduced efficiency η_A. At a distance of about $1.8\,\mathrm{km}$ the telegram must be split up into two packets to maintain the required energy on the receiver side. The efficiency for both transmissions is averaged. The behavior of $\eta_{B,C}$ is inverse to $\eta_{A,D}$ caused by growing η_C with raising E_{TX}. Furthermore, $\eta_{B,D}$ is independent of E_{TX}.

Using the calculated efficiencies, the number of transmissions for a given capacity of the battery can now be estimated. The influence of the raising output impedance of the battery with lowering capacity of the cell is neglected. Tab. 1. lists the possible number of transmissions assuming a cell with $30\,\mathrm{mAh}$ at $3\,\mathrm{V}$ [10]. The parameters for this calculation are the same as in Fig.2.

TABLE I
NUMBER OF TRANSMISSIONS FOR THE DIFFERENT POWER CONCEPTS WITH A BATTERY CAPACITY OF $30\,\mathrm{mAh}$

$Distance$[km]	$\eta_{A,C}$	$\eta_{B,C}$	$\eta_{A,D}$	$\eta_{B,D}$
1	1.590.800	1.294.100	2.018.400	1.636.200
2	138.400	126.800	154.200	142.400
3	33.200	31.000	36.400	34.100
4	12.000	11.300	13.200	12.400
5	5.500	5.200	6.000	5.600

IV. Hardware Demonstrator

In order to deliver a proof of concept, we developed a miniaturized TX node in a cubic form with an edge length of $10\,\mathrm{mm}$. It is powered using a CR1025 coin cell battery with a total energy of $30\,\mathrm{mAh}$ [10]. Due to the best efficiency results, concept (A,D) was implemented. For future work we will use this demonstrator to validate our calculations.

V. Summary

In this paper different power concepts utilizing small batteries for long range telemetry links are discussed. A range calculation shows that it is possible to reach a distance of $5\,\mathrm{km}$ between TX and RX in urban environments. Concept (A,D) leads to the most realizable transmissions due to the highest efficiency of all considered concepts. Using our miniaturized hardware demonstrator of a TX, we will validate our calculations.

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