

Improving Throughput Performance under an Energy Efficient Multiplexing Access Scheme using Time-of-Failure Prognosis

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ABSTRACT

With the rise of Smart Cities and e-Health, along with the ongoing pursue for higher performing wireless networks, a field that has gained attention is Body Area Networks (BANs). One of the main thrusts of BANs is health-related applications, but these networks have a broad range of functionalities. One concern is supplying enough energy to support an active network. There are various designs that satisfy this demand, but an attractive option is the use of energy harvesting devices (EHDs). Typically, an EHD cannot match the energy consumption of a BAN, but there are schemes that can achieve energy self-sustainability at the cost of reducing the throughput. Using prognosis techniques, the time of failure (ToF) can be estimated and the Process-Stacking Multiplexing Access (PSMA) can transmit at specific rates when the ToF is at a predefined range. This can significantly increase the throughput at the cost of energy. This energy is a calculated investment that is expected to be replenished with the objective of not depleting the battery during active periods. Results show that prognosis can significantly increase the throughput.

Categories and Subject Descriptors

C.2.1 [Network Architecture and Design]: Wireless communication – *body area network, remote antenna unit, relay node.*

C.2.2 [Network Protocols]: Protocol architecture – *multiplexing access, energy efficient, time of failure, prognosis.*

General Terms

Algorithms, Measurement, Performance, Design, Human Factors, Experimentation.

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Keywords

Body area networks, energy efficiency.

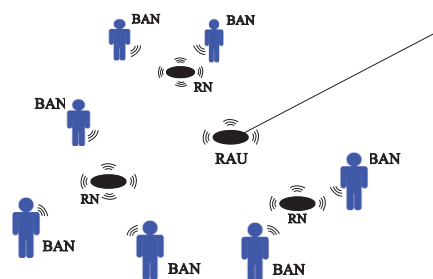


Figure 1. WPAN composed of BANs, relay nodes and a remote antenna unit.

1. INTRODUCTION

Various emerging technologies are rising with high expectations of unification and greater performance, such as Smart Cities and e-Health. Wireless networks play a fundamental role in this growth, arguably the greatest catalyst of these technologies, bringing mobility and portability to a wired and fixed-location topology. This has enabled a wide range of wireless networks, such as cellular networks, wireless local area networks (WLANs), wireless personal area networks (WPANs), and body area networks. This quick paced evolution points toward smaller cells with greater bandwidth capacity, resembling that of Fig. 1. This bandwidth has an inherent trade-off component that is range. Some examples of this are: LTE [1] (cell size: kilometer, throughput: 300 Mb/s), WiFi [2] (cell size: hundreds of meters, throughput: 600 Mb/s), WPAN [3] (cell size: tens of meters, throughput: 2.5 Gb/s). The throughput of this last example (WPAN) is achieved using 60 GHz millimeter-wave modulation. These extremely high frequency (EHF) modulation schemes are becoming more common and only have a several meters range. Time-based multiplexing access is a convenient choice for small cells. This allows the few users (possibly one) in range to use the entire available spectrum. This is one reason that the ECMA-387 standard [4] only specifies four sub-bands.

PSMA is a time-based multiplexing technique [5]. It has a unique method of multiplexing that efficiently utilizes transmission time. Its stacking scheme has the flexibility to perform QoS, differentiated services, and other techniques. One particular

benefit of PSMA, which is of interest to this work, is its ability to charge (when the node is equipped with an EHD) by “scheduling” idle times. In [5] there is a description of an algorithm that supports energy self-sustainability – the ability to run without an external source of energy. The trade-off is a decrease of throughput. This drawback can be diminished by implementing prognostic techniques, such as those described in [6].

This document is organized in four sections, including the introduction. Section 2 provides some basic principles related to this work, more specifically, it explains briefly PSMA and the prognosis algorithm. Section 3 presents the results and discussions. The conclusion is found in Section 4.

2. Basic Principles

2.1 Process-Stacking Multiplexing Access

PSMA, like TDMA, perform multiplexing access in the time domain. PSMA schedules processes; this means that time is reserved when requested and for the time requested. To organize transmissions a global time pointer is used. In the event that a process or node requests the use of the antenna, this process is scheduled at the time stored in the global pointer and the pointer is shifted by the amount of time requested, in practice a buffer time is also inserted. If the current time reaches the global pointer time, then the node switches to listen mode. The end result is a series of stacked requests, as shown in Fig. 2.

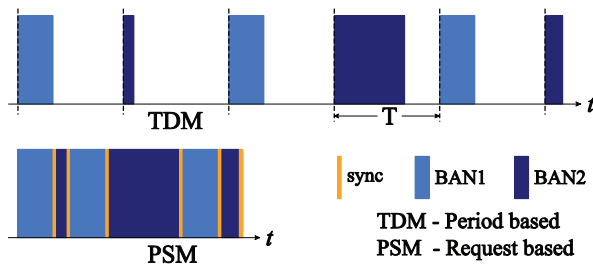


Figure 2. Comparison of time division multiplexing versus process-stacking multiplexing.

2.1.1 Energy Self-sustainability Support in PSMA

Energy efficiency is an essential property of any wireless system. Self-sustainability is an attractive quality that frees the nodes from a fixed power supply. To support self-sustainability a node must possess an energy harvesting device. Using PSMA an idle process can be inserted in a cyclic manner to help restore battery loss. The following equation describes how to compute the necessary sleep time needed to attain self-sustainability.

Self-sustainability condition:

$$T_{SSS} = T_{sleep} = \frac{(P_{tx} - P_{eh})T_{tx} + (P_{rx} - P_{eh})T_{rx}}{P_{eh} - P_{sleep}} \quad (1)$$

P_{tx} , P_{rx} and P_{sleep} are the consumed power values for the transmitting, receiving and sleep states, respectively. P_{eh} is the charging rate, and T_{tx} and T_{rx} are the maximum transmitting and receiving slot times, respectively. A self-sustainable system (SSS) is achieved by selecting the appropriate value for T_{sleep} . This is a simplification of the expression derived in [5], where the omitted states are assumed to have negligible time intervals. This scheme has been proposed in related work [7][8].

2.2 Particle-filter-based Prognosis

This prognosis algorithm is based on sequential Monte Carlo (SMC) methods, also referred to as particle filter (PF), which are a class of algorithms designed to obtain samples sequentially, i.e., generate a collection of weighted random samples. The most basic SMC implementation (the sequential importance sampling particle filter) computes the value of the particle weights by setting the importance density function equal to the a priori probability density function (pdf) for the state. The weights for the newly generated particles are evaluated from the likelihood of new observations. The efficiency of the procedure improves as the variance of the importance weights is minimized.

Adaptive prognosis schemes require the existence of a fault dimension. The evolution in time of the fault dimension can be described through a nonlinear state equation [9]. By using the aforementioned state equation to represent the evolution of the fault dimension in time, it is possible to generate long term predictions using kernel functions to reconstruct the estimate of the state pdf in future time instants. The resulting predicted state pdf contains critical information about the evolution of the fault dimension over time. One way to represent that information is through the computation of statistics (expectations, 95% confidence intervals), and either the Time-of-Failure (TOF) or the Remaining Useful Life (RUL) of the faulty system [9]-[11]. The derivation of the state of charge (SoC) prognosis expression can be found in [6], the final expression is then:

$$R^{\frac{RUL}{\delta_T}} x_2(t_p) - (V_o - \alpha I - 1)I\delta_T 10^{-5} \frac{R^{\frac{RUL}{\delta_T}} - 1}{R - 1} = 0 \quad (2)$$

Where $RUL = TOF - t_p$, δ_T is the sampling rate, $R = 1 + eI\delta_T 10^{-5}$, e is a constant that characterizes the battery voltage drop in terms of remaining SoC, V_o is the battery's initial voltage, I is the current (assumed constant), α is the battery's instantaneous internal resistance (assumed constant), and $x_2(t_p)$ is the state of charge at the prediction time. Solving this expression for TOF yields the time of failure, in this case the complete charge depletion time.

2.2.1 PF-based Prognosis in PSMA

PSMA can benefit from PF-based prognosis. The SSS does not need to run fully at all times (or ever). If the prognostic determines the TOF , complete discharge in this context, it can compute a T_{sleep} that will not drain the battery in a preconfigured amount of time. This process can be performed periodically, to dynamically adjust the sleep time. By doing so, it can significantly increase the overall throughput. Fig. 3 illustrates that varying T_{sleep} will affect the prediction of TOF . No SSS means that $T_{sleep} = 0$, full SSS means the T_{sleep} value is given by (1), and partial SSS is any value of T_{sleep} within this range.

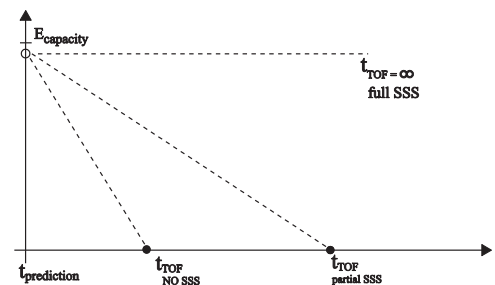


Figure 3. Inter-process communication in the BAN.

3. Results and Discussion

3.1 Battery Model

To determine the benefits of adding a SoC prognosis algorithm to PSMA a series of experiments and simulations were performed. The first step is to find a suitable model for the battery voltage versus SoC. A simple testbed is setup to measure the voltage and current changes as time progresses until the charge is completely drained. A Li-Ion battery (LiFePO₄) was drained while measuring the voltage and current changes in time. The energy and the battery's internal resistance are also obtained from these measurements. The battery's initial voltage V_o is 2.4 V. The results are shown in Fig. 4.

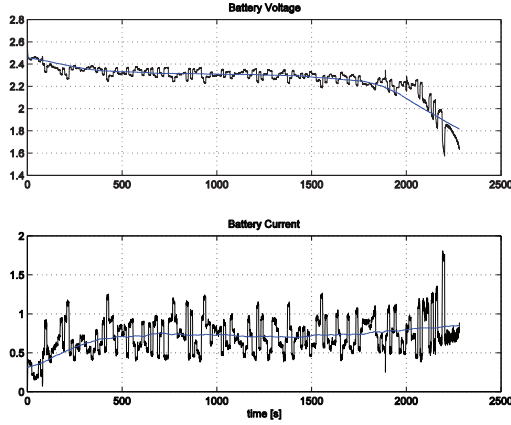


Figure 4. Battery voltage and current during drainage.

To obtain the battery model the data is filtered using an averaging sliding window and a regression is obtained. The regression is performed using the following expression as a basis:

$$\frac{V_{damp}(t_p) - V_{mid}}{e^{K_1 SoC(t_p)}} e^{K_1 t} + V_{mid} + \frac{V_{damp}(TOF) - V_{mid}}{e^{K_2 SoC(TOF)}} e^{K_2 t} \quad (3)$$

V_{damp} is the filtered version of the voltage measurements. K_1 , K_2 , and V_{mid} are the constants that are used to reduce the mean square error (MSE) and obtain the regression, and therefore a battery model. The model parameters are summarized in Table 1. The current model can be obtained in the same manner by replacing V_{damp} and V_{mid} with I_{damp} and I_{mid} , respectively.

Table 1. Battery Model Parameters

Parameter	Voltage	Current
K_1	0.13	0.15
K_2	-0.105	-0.11
$\{V, I\}_{mid}$	2.32 V	0.73 A

The filtered voltage data and regression are shown in Fig. 5. It can be observed that it shows a high degree of agreement.

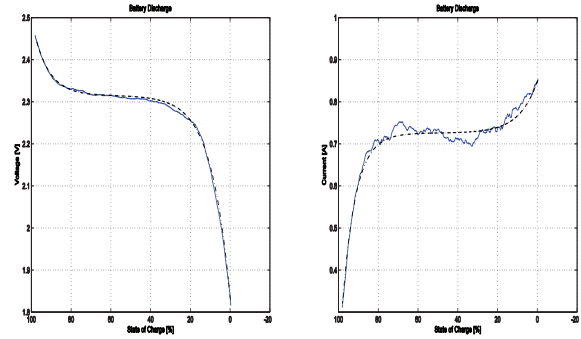


Figure 5. Voltage (left) and current (right) filtered data (solid) and regression (dashed).

As mentioned previously, the current I is assumed to be constant in the TOF calculations, but the model shows the current is relatively constant during the middle 60% of the discharge. It can be argued that this is the critical zone, since the nodes can be configured to work at maximum capacity ($T_{sleep} = 0$) during the initial 20% of the charge, where the consumption of energy is less critical, and initiate predictions below the 80% threshold. The final 20% region will yield error but it will tend to underestimate TOF , which is considered safe.

3.2 PSMA with SoC Prognosis Simulation

To portray the advantages of implementing SoC prognosis into PSMA a simulation is programmed such that the battery energy discharge rate is a function of T_{sleep} . As observed in Fig. 5, the voltage discharge is not linear, nevertheless the energy discharge is assumed to be linear (empirical data shows it is approx. linear). Using the model obtained, the energy discharge behavior is converted to voltage and current. This data is used to compute the SoC prognosis. To compute the energy discharge the values of Table 2 are used, which are the same as those used in [5]. A level of uncertainty (noise) is added to match the behavior observed during battery discharge (see Fig. 4). This data is then used to compute the prognosis. Fig. 6 shows the SoC prognostic results. The actual data crosses the depletion threshold at time 2200 s and the prognostic estimated (when it was at 80% charge) that the TOF would occur at time 2123.5 s, an error of 3.5%.

Table 2. Simulation Parameters

Description	Value
system supply voltage	3 V
time in sleep mode	0-10000 ms
max unit length of time slot	8.3 ms
energy from harvesting	100 uJ/s
energy capacity of battery	5 Joule

Operation Mode	Power
RM Sleep	0.06 mW
SM Sleep	0.9mW
Synchronization	6 mW
Idle listen	3 mW
Receiving	9.3 mW
Transmitting	9.9 mW

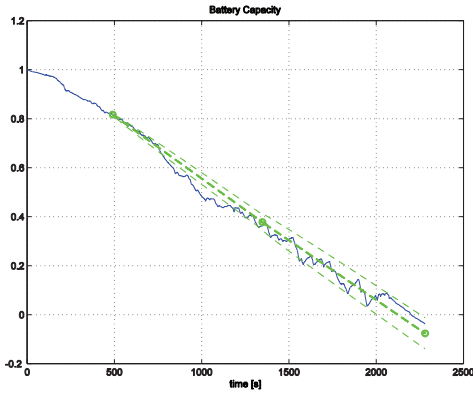


Figure 6. SoC Prognosis of PSMA using $T_{sleep} = 0$.

3.3 Throughput Improvement Demonstration

After showing that the SoC prognosis produces high degree of confidence predictions it is necessary to explain the benefit of its implementation. To do this the value of T_{sleep} was varied from 0 to $T_{SSS} = 671\text{ms}$ (full SSS as given by (1)) and the TOF predicted by the SoC prognosis algorithm is obtained (estimated at 80% charge), shown in Fig. 7. In a similar way the throughput is obtained (with varying T_{sleep}), shown in Fig. 8.

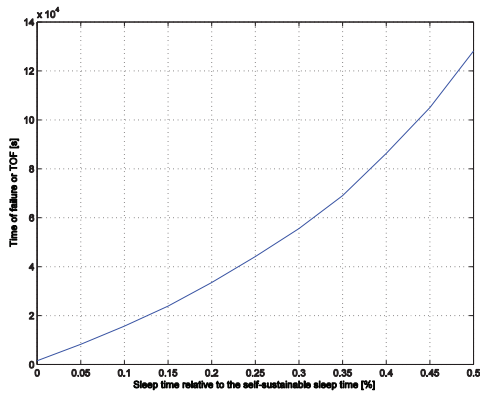


Figure 7. TOF prediction with varying T_{sleep} .

This implies that PSMA can be configured to dynamically adjust T_{sleep} based on the prediction. The specific design can vary with the application. A trivial example is that if the node requires 8 hours of active operation it would have to operate at approx. 30% of T_{SSS} (from Fig. 7), which implies it can transmit at $\sim 60\text{ Mb/s}$ (from Fig. 8). This improves the throughput by a factor of 5 with respect to running at T_{SSS} . Another application example is to dynamically adjust T_{sleep} by maintaining the TOF fixed to a particular time of the day. If the TOF < target time, then the value of T_{sleep} can be increased, inversely if TOF > target time the value of T_{sleep} can be reduced. This will guarantee that the node will not depleted the battery before the target time while working at the highest capacity possible.

4. Conclusion

The proposed PSMA can self-sustain renewable nodes in a BAN. The SoC prognosis can accurately predict the TOF (charge depletion time in this context). A battery model was obtained from experimentation using a Li-Ion (LiFePO_4) battery, and was used to simulate the voltage and current characteristics during the

battery charge depletion. In an example considered in the paper, the SoC prognosis showed that the throughput performance could be increased by a factor of 5, with an 8 hour frame of guaranteed energy.

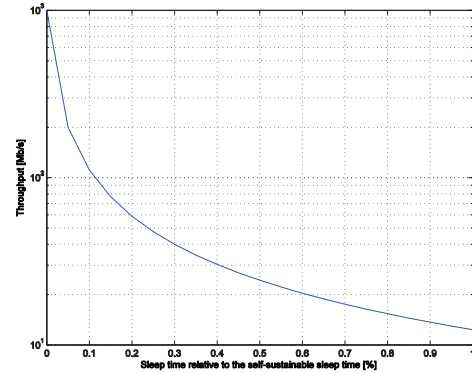


Figure 8. Throughput obtained versus T_{sleep} .

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