SoC control for improved battery life and throughput performance under VST-TDMA

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Energy independence is a wireless device quality that demands the utmost exigency. Energy harvesting devices (EHD) alleviate the energy constraints demanded by these nodes and with the use of protocols, such as variable slot time-time division multiple access (VST-TDMA) energy self-sustainability can be attained at the cost of throughput. To allow high throughput levels and self-sustainability the system can allow the power consumption to be greater than the energy harvesting rate while a state-of-charge (SoC) of 30% or greater is maintained. To achieve this the system must accurately estimate the SoC, which is not a trivial task. In this work, a battery model is incorporated into the VST-TDMA protocol to estimate the battery model parameters, including the SoC, which successfully allows it to maintain appropriate SoC levels.

Introduction: In wireless communications, having energy-self-sustainable nodes is a challenging and on-going research topic. Complete energy independence is hardly achievable due to limited energy-harvesting capabilities and battery degradation. Possibly, today, this is an unattainable characteristic in communication systems but, through smarter decision making, the media access control (MAC) protocol can efficiently utilise low-power energy-harvesting devices (EHDs) and simultaneously extend the life of the battery. These objectives are the drivers of this work. The VST-TDMA [1] is a MAC protocol designed with the flexibility and versatility to handle this systematic process. This protocol, with the incorporation of battery status information and an accurate battery-energy model, can estimate the battery depletion time and, as a corollary, avoid consuming the entire charge. Reaching a high depth of discharge (DOD) level causes some harmful irreversible chemical effects on lithium ion batteries that consequently increases the battery's degradation rate, hence, decreasing its useful life [2, 3]. Empirical results show that $LiFePO_4$ cells have a deleterious intercident DOD level between 50–60% [2], and for lithium-metal-polymer there are two observable discontinuities, between 50–60% and between 70–80% [3].

Table 1: State transition model and measurement equation variables

Variable	Description
$x_1(k)$	Internal impedance estimate at time k
$x_2(k)$	State of charge estimate at time k
$\omega_1(k)$	Process noise (AWGN added to internal impedance)
$\omega_2(k)$	Process noise (AWGN added to state of charge)
$\eta(k)$	Process noise (AWGN added to voltage)
$v(k)$	Battery voltage at time k
$i(k)$	Battery discharge current at time k
Δt	Sampling time
E_{crit}	Maximum nominal energy delivered by the energy storage device
v_L	y-intercept of voltage discharge curve (in Zone 2 [4])
v_0	Open circuit voltage when the battery is fully charged
α, β, γ	Additional battery model parameters

Battery energy model: The selection of an accurate and highly configurable model is imperative for the correct systematic operation and prognosis of the control system. There are several accepted models by the prognostic and health management research community [4, 5], which are consolidated by combining the energy depletion behaviour at different stages. A model that has manipulable parameters for distinct SoC stages, idoneous for this work, is presented in [4] and included below:

State transition model:

$$x_1(k+1) = x_1(k) + \omega_1(k) \tag{1}$$

$$x_2(k+1) = x_2(k) - v(k)i(k)\Delta t\, E_{\text{crit}}^{-1} + \omega_2(k) \tag{2}$$

Measurement equation:

$$\begin{aligned} v(k) = {} & v_L + (v_0 - v_L)\mathrm{e}^{\gamma(x_2(k)-1)} + \alpha v_L(x_2(k)-1) \\ & + (1-\alpha)v_L\left(\mathrm{e}^{-\beta} - \mathrm{e}^{-\beta\sqrt{x_2(k)}}\right) - i(k)x_1(k) + \eta(k) \end{aligned} \tag{3}$$

See Table 1 for variable description. α, β, and γ are design parameters that determine the voltage behaviour as the battery is discharged. Each battery has a unique set of values, furthermore, the set changes in every charge cycle. For this reason, dynamic control and prediction is highly beneficial to the node's energy management system.

VST-TDMA energy management system: VST-TDMA [1] is a MAC protocol that efficiently schedules the surrounding nodes. It does this in a manner that the idle time of the base station is negligible insofar as there are any pending transmissions queued (in any direction). It is also very energy efficient, as it eliminates the listen mode in the nodes, hence, the nodes are only active when engaging the effective modes (transmission, reception, or synchronisation). One of the most outstanding attributes of VST-TDMA is its cross-layer solution between the energy management and time management schemes. The result of this layer cross-over is that the available energy has an impact on the scheduling frequency, which directly affects the effective throughput. The overall effect is that a node with low energy will transmit at a slower rate. If the node is equipped with an EDH, the protocol can slow down the transmission to reach an energy balance. The following expression specifies the minimum sleep time that must be introduced to achieve energy self-sustainability [1].

$$t_{sss} = \frac{\sum_{n\in\text{state}} \left(P_n^{\odot} - P^{\otimes}\right) t_n^{\odot}}{P^{\otimes} - P_{\text{sleep}}^{\odot}} \tag{4}$$

The energy harvesting rate is given by $P^{\otimes}$ and the power of the discharge states is denoted by $P_{\text{state}}^{\odot}$, except for the power consumed by the sleep state, which is denoted by $P_{\text{sleep}}^{\odot}$. The same notation is used for the time (i.e. harvesting time $t^{\otimes}$ and consumption times $t_{\text{state}}^{\odot}$ or $t_{\text{sleep}}^{\odot}$). The sleep time expression assumes that the system is continuously harvesting energy, i.e. $t_{\text{Total}} = t^{\otimes} = \sum_{n\in\text{state}} t_n^{\odot} + t_{\text{sleep}}^{\odot}$ and that the discharge power of every individual state is greater than the energy harvesting rate, with the exception of the sleep state. Therefore, $P^{\otimes} > P_{\text{sleep}}^{\odot}$ and $P_{\text{state}}^{\odot} > P^{\otimes}$ (true for all states). Though (4) yields the optimal time value for energy independence, i.e. balancing harvesting and consumed energies, this selection produces low throughputs. Energy self-sustainability is a trade-off for throughput, nevertheless, it is not necessary to operate in the energy-self-sustainability mode at all times. When found in a high energy state nodes can operate at higher rates, slowly decreasing the throughput as energy is consumed reaching t_{sss} when the SoC reaches the minimum allowed SoC ($x_{2\,\text{min}}$). This minimum SoC protects the battery from rapid degradation, extending its life. The dynamic variation of the sleep time is a straight-forward proportion between the sleep time and the DOD, which is a reasonable general solution that does not incorporate specific usage patterns.

$$t_{\text{sleep}}(k) = t_{sss} \cdot \frac{1 - x_2(k)}{1 - x_{2\,\text{min}}} \tag{5}$$

As a result of the dynamic adjustment of the sleep time, the current drainage behaviour is modelled by

$$i(k) = \frac{\sum_{n\in\text{state}} i_n}{N_{\text{states}}} \left(\frac{x_2(k) - x_{2\,\text{min}}}{1 - x_{2\,\text{min}}}\right) \tag{6}$$

which is the current used to compute $v(k)$ and to update $x_2(k+1)$. N_{states} is the total number of states, i.e. $N_{\text{states}} = \sum_{n\in\text{state}} 1$. Observe that when $x_2(k) = x_{2\,\text{min}}$ the overall current is zero. This is expected as the harvesting current and energy draining currents are at perfect balance (equal), when $t_{\text{sleep}}(k) = t_{sss}$.

Objective and methodology: The goal is to avoid reaching a SoC below $x_{2\,\text{min}}$, which in practice is harmful and greatly diminishes the battery's overall life. This is achieved by two means: (i) effective control of the sleep time implemented by VST-TDMA and (ii) by successfully estimating the parameters that characterise the battery, which are α, β, γ, v_0, v_L, and most importantly x_2. The estimation is done periodically at intervals Δt and the calculation is done with a log of recorded currents and voltages. Since there are six parameters that need to converge, it is unpractical to use an exhaustive search. A low-computational-overhead heuristic approach is used. The process initiates by selecting N (an odd number ≥ 3) points per parameter per iteration within the range of the parameter. The distance between point is called the step δ, where the maximum step $\delta_{\max}$ is the entire searchable range divided by $N-1$. The value that reduces the error is selected to be the middle point of the next iteration, where N new equidistant points are selected. The distance between the points is determined by a confidence index unique to each parameter, the greater the confidence index the lower is the distance between points. When the middle value is selected the confidence index is increased; when an edge value is selected the confidence index is reduced; else, the confidence index remains unchanged. The confidence index is $C = 1 - (\delta/\delta_{\max})$. The confidence index has a confidence multiplicative factor (CMF). Because the node is oblivious to the nominal values, an increase in the confidence index does not necessarily imply that the estimation is approaching the nominal value. An increase in the confidence index implies that the estimation does not vary with subsequent iterations, ideally because the nominal value is reached. The initial values are randomly selected within a reasonable range, except x_2 which it is always assumed to start at 100%.

Results: To observe battery conservation behaviour of the VST-TDMA protocol a scenario with a persistent (non-stop) transmission is considered. Two cases are simulated: SoC control (i) with parameter estimation and (ii) without estimation. The main objective is to avoid reaching a DOD greater than 70% (or SoC lower than 30%). No other schemes are compared because, to the best of our knowledge, this is the first work that considers SoC control under the VST-TDMA protocol. The simulation parameters are shown in Table 2.

Table 2: VST-TDMA system, battery, and control simulation parameters

System parameters		Battery model and control parameters		
Parameter	Value	Parameter	Nominal	Initialised as
$x_{2\,\min}$	30%	$x_2(0)$	80%	100%
$x_1(0)$	0.3 Ω	v_0 [4]	3.58 V	3.40 V
i_{Tx} [1]	2.765 mA	v_L [4]	3.46 V	3.29 V
i_{Rx} [1]	2.6 mA	α [4]	0.08	0.15
i_{Sleep} [1]	16 μA	β [4]	16	22
i_{EH} [1]	28 μA	γ [4]	19.65	15
Δt	$10{\cdot}10^4$s			
E_{crit} [4]	20,127 J	Parameter	Value	
ω_1	−40 dB (x_1)	N	5	
ω_2	−40 dB (x_2)	CMF	2	
ν	−40 dB (v_0)			

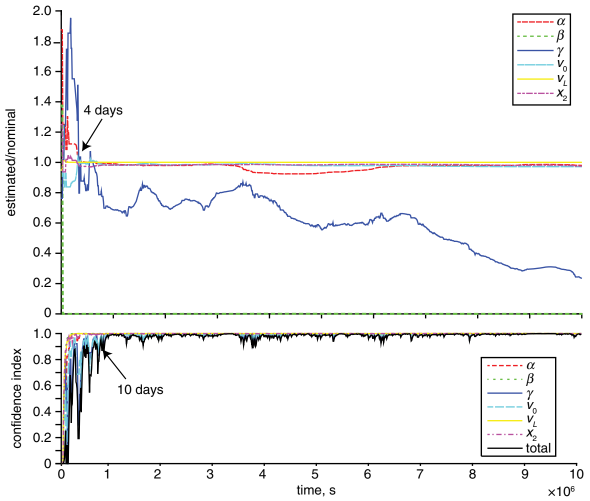

Fig. 1 *Estimated-nominal ratio and confidence index against time*

Even through a low-complexity heuristic error minimisation technique is implemented, after approximately 4 days (see Fig. 1) the estimation algorithm has accurately obtained the nominal values within ±5% with the exception of γ and β. The total time graphed is equivalent to 115 days. β is a value that describes the drop of energy after E_{crit} energy has been consumed. Because the system is equipped with an EHD the battery never reaches this zone and therefore it cannot estimate β. Similarly, γ describes the initial behaviour, when the battery is fully charged. Since the SoC state starts at 80% the initial zone or region, where γ has the greatest effect, is skipped preventing the system from accurately estimating γ. Nevertheless, the system is able to estimate the remaining parameters, which are sufficient to obtain the SoC. The total confidence index is $C_{\text{Total}} = C_\alpha C_\beta C_\gamma C_{v_0} C_{v_L} C_{x_2}$. Even though, after 4 days the system converged, it is not 90% confident until after 10 days. If the node is incognizant of the battery model parameters, even if there is an algorithm to protect the battery from reaching low SoC values the device will not be able to accomplish this. In the scenario described, the initial SoC is 80%. The traditional VST-TDMA algorithm assumes that the initial SoC is 100% and therefore it allows a 70% discharge, but this causes the energy to reach a SoC of 10% causing irreversible damage to the battery. In the scenario with the battery model parameter estimation it can be observed that the SoC estimation varies between 70 and 80% before stabilising. Once stabilised, the proposed technique successfully maintains the actual SoC above the 30% level, as seen in Fig. 2.

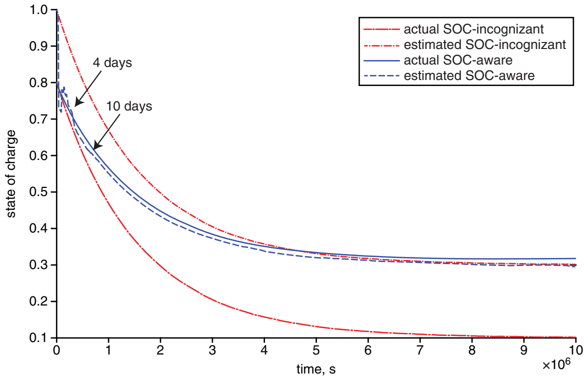

Fig. 2 *State of charge against time*

Conclusion: In wireless communication, energy conservation and battery life span lengthening are critical aspects that impact the overall performance of the system. VST-TDMA has energy self-sustainable capabilities but before this work it was incognizant of the SoC, which is essential to extend the life of the battery. An accurate battery model can help estimate the battery model parameters, including the SoC. Incorporating a battery model, VST-TDMA is able to estimate the battery model parameters by monitoring the current and voltage consumption of the device. More importantly, the system is able to estimate the SoC and maintain it above 30%. This can significantly extend the life span of the battery, allowing the wireless device to have greater independence.

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One or more of the Figures in this Letter are available in colour online.

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