A Power Manager with Balanced Quality of Service for Energy-Harvesting Wireless Sensor Nodes

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Abstract

Future Internet of Things is paving the way for the proliferation of Wireless Sensor Networks (WSNs). To overcome the limited energy in batteries, WSN nodes are relying on everlasting environmental energy. Moreover, a Power Manager (PM) is also embedded in each WSN node to guarantees that the total consumed energy is equal to the harvested energy for a long period, leading to Energy Neutral Operation (ENO) with a theoretically infinite lifetime. In this paper, a new PM for WSN nodes powered by periodic sources (e.g. ambient energy is not available during the full harvesting cycle) is proposed. Not only respecting the ENO condition, our PM is able to balance the Quality of Service (QoS) during the whole cycle to provide regular data tracking, which is essential for WSN applications like monitoring. Simulations on OMNET++ show that our PM can improve the QoS during the absence of energy by a factor up to 84% compared to state-of-the-art PMs, while guaranteeing the same global QoS.

Categories and Subject Descriptors

C.4 [**Performance of Systems**]: Measurement Techniques; C2.4 [**Computer Systems Organization**]: Computer Communication Networks—*Distributed Systems*

General Terms

Algorithms, Performance, Measurement, Power management

Keywords

Wireless Sensor Network, Energy neutrality, Energy harvesting, Adaptive duty cycle

1 Introduction

The development of wireless objects in our living spaces such as mobile phones, RFID tags, home appliances or monitoring cameras has opened a future Internet, which is referred as Internet of Things (IoT) [1]. Identified by a unique address, any wireless object is able to join the network and communicate with others, as traditional computers through Internet, based on standard communication protocols [15]. IoT is opening a novel opportunity for the proliferation of Wireless Sensor Networks (WSNs), which can provide a wide range of monitoring applications in some places where cables are difficult and costly to draw. However, battery maintenance becomes a burden for many WSN applications (e.g. large factories, dangerous places), which opens two different approaches in extending system lifetime. In the first one, a variety of methods and techniques to reduce power consumption such as using nano-watt wake-up radio receivers [8] and efficiently scheduling MAC protocols[2] have been proposed. Although system lifetime is improved, it is still crippled by the limited energy in the batteries, used as the storage devices. In a second approach, environmental energy sources have been integrated to supplement, or even replace batteries. Thanks to advancements in energy harvesting techniques, everlasting environmental energy can be extracted and brings a breakthrough to design completely autonomous WSNs. A wide range of harvesters, which are cheap, tiny, and high power density, have been proposed and can be applied into WSNs such as photovoltaics for solar energy [16], thermoelectric for thermal energy [12] or wind generator for airflow energy [5].

Energy harvesting capability has opened a new paradigm for designing a power manager (PM) in WSN nodes. Instead of minimizing the consumed energy to maximize system lifetime [18] as in battery-powered WSN, the PM makes the harvesting node work in Energy Neutral Operation (ENO) [11], which means that consumed energy is equal to harvested energy for a long period. This strategy can provide a theoretically infinite lifetime (until its hardware is outdated), which is required for an autonomous WSN. While following the ENO condition, the average energy consumed by the node is adapted according to its harvested energy. Among various adaptive techniques such as dynamic voltage and frequency scaling [17], power transmission management [7], duty-cycling by changing wake-up interval of the node is the most popular approach since it has a direct impact on the MAC protocol, which is the dominant consumed source in

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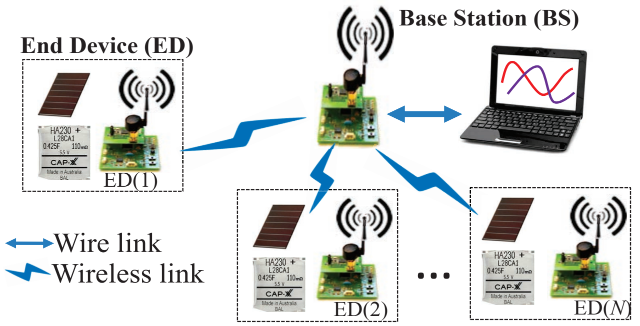

Figure 1. Single hop autonomous WSN used in this work. Multiple End-Devices (EDs) collects data and then, send to a Base-Station (BS).

the WSN node [2]. Moreover, behaviors of environmental sources should be considered in policies of the PM. While fluorescent light in hospitals or heat from industrial machines provides almost continuous power with rarely interruptions, solar or indoor light energy in an office are often periodic with an absence of energy followed by an energy interval. In order to guarantee continuous operations, the PM must propose strategies to reserve harvested energy before it is no more available.

In this paper, we present a novel low complexity Balanced Quality of Service-based Power Manager (BQS-PM), designed for autonomous WSN nodes powered by periodic energy sources. In these kinds of energy sources, harvested energy is only available during the energy harvesting interval (T_{EI}) while there is no more harvested energy in the non-energy harvesting interval (T_{NEI}). This behavior is repeated every cycle $T_C = T_{EI} + T_{NEI}$. Not only satisfying the ENO condition, BQS-PM is also able to balance the performance of the node (or Quality of Service QoS) during the whole cycle by considering the ratio between T_{NEI} and T_{EI}. This feature is really useful for monitoring applications, which usually require regular data tracking. Performance of BQS-PM is simulated in OMNET++ with a single-hop network, as in Fig. 1, and compared with other PMs.

The rest of this paper is organized as follows. In Section II, related works are presented, followed by the architecture of the autonomous WSN node powered by ambient energy. The detail of BQS-PM is proposed in Section IV. Simulations and performance comparisons are presented in Section V. Finally, the paper ends with conclusions in Section VI.

2 Related Works

Kansal et al. [11] proposed a low complexity PM (KAN-PM) for dynamically adapting the duty cycle of a solar-powered and battery-based WSN node. Their approach takes advantage of the periodic solar energy source when photovoltaics (PVs) are used in an outdoor environment. Indeed, the harvested power can be predicted from previous samples using an Exponential Weighted Moving Average (EWMA) filter. A cycle lasting for a day is divided into fixed slots of 30 minutes and adaptation calculations are performed at the end of each slot. To ensure ENO condition, the residual energy (the difference between the predicted energy and the real one) of the previous slot is used to adapt the duty cycle in future slots. However, when there is a change from a sunny to a cloudy day or vice versa, KAN-PM performs poorly since duty cycle of the node is mostly adapted from historical harvested power profiles. Another disadvantage of KAN-PM is that its adaptations do not take into account the State-of-Charge (SoC) of the battery used for the energy storage. Therefore, if the node is deployed with a low SoC and the energy predictor produces a negative error (e.g. from a sunny to a cloudy day), the SoC can be less than a minimum level after a day and the node operations is interrupted. Moreover, the objective of KAN-PM is only to maximize instead of balancing the QoS during a whole day. As a consequence, the autonomous node usually has a high QoS during day-time, when there is plenty of harvested energy, but very low QoS during night-time, when there is no more harvested energy.

Castagnetti et al. [6] presented the Close-Loop Power Manager (CL-PM) which improves the throughput of a WSN node up to 50% compared to [11]. Duty cycle of a WSN node is determined from the current amount of harvested energy, which is approximated by a function of the light intensity using a luminance sensor (expressed in lux). Therefore, the issue when changing from a sunny to cloudy day or vice versa in KAN-PM is avoided in CL-PM. Moreover, the battery SoC is considered in CL-PM, not only to increase the QoS during the night-time but also to guarantee that the SoC is always greater than a minimum value for continuous operations. Another improvement in CL-PM is the use of a dynamic adaptation period, instead of a fixed one as in KAN-PM, to trade-off between the overhead computations and the reactivity of the power manager. However, the wake-up interval of the node is computed by a ceil function of the output produced by an energy neutral power manager. As this function always returns a small integer value, which is higher than the real neutral value, there is always a small part of harvested energy that is used to charge the battery. It means that the voltage of the battery is slightly increased during the day and, to satisfy ENO after a day, the QoS during the night must be reduced. In consequence, CL-PM provides an unbalanced QoS during a whole day, as it is the case in KAN-PM.

In this paper, a new Balancing Quality of Service-based Power Manager (BQS-PM) is proposed. This PM not only satisfies the ENO condition, but is also able to balance the QoS during a whole cycle of a periodic energy source (e.g. light energy in an office). By considering the ratio between two intervals in a cycle (T_{EI} and T_{NEI}), plenty of harvested energy can be reserved. Therefore, the average QoS when there is an absence of energy (T_{NEI}) can be balanced with the interval when harvested energy is available (T_{EI}).

3 Autonomous WSN Node Architecture

The architecture of an autonomous WSN node powered by ambient energy is presented in Fig. 2. The energy adapter is designed to deal with different outputs of various harvesters. While indoor/outdoor photovoltaics provide high voltage but low current, thermal electric generators output low voltage but high current. Meanwhile, wind turbines produce an AC output, which also needs to be adapted. In this

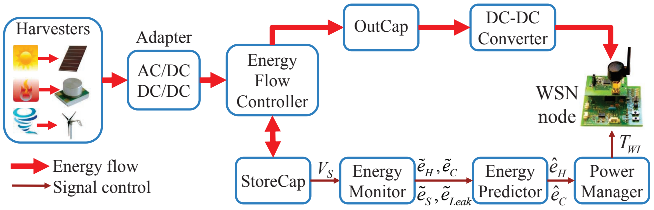

Figure 2. Autonomous WSN node architecture.

work, when the light energy in an office is used to demonstrate a periodic energy source, only a resistor is required for the energy adapter. Then, harvested energy is distributed by the energy flow controller to the two capacitors OutCap and StoreCap, which are used for energy storages. All harvested energy directly charges OutCap for powering the WSN node through a DC/DC converter. As soon as OutCap is fully charged, StoreCap is allowed to be charged. This architecture, which has been shown in [12], can provide a fast booting capability and a more durable storage than a rechargeable battery-based system.

In order to provide energy-aware capability, an energy monitor is designed for each autonomous node. It can be implemented by hardware [16] or software [6] components. Although hardware-based energy monitors avoid the platform dependencies of software-based approaches, they require additional hardware components (e.g. low-power IC monitor DS2438 in [16]). Moreover, software energy monitors can provide a precise energy consumption of the WSN node by using a look-up table characterizing energy for each atomic activity of the node [6]. Therefore, the supercapacitor-based energy monitor proposed in [12] is used in this work to provide the energy profiles for adaptations of the power manager, including the harvested ($\tilde{e}_H$), consumed ($\tilde{e}_C$), leakage ($\tilde{e}_{Leak}$) and available energy ($\tilde{e}_S$) in StoreCap. This energy monitor only needs to read the voltage of the StoreCap and to keep tracking activities of the wireless node to provide the estimation of energy profiles

In order to design an effective PM, an accurate energy predictor, which estimates the potential harvested energy ($\hat{e}_H$) in the near future, is also required. Based on several historical values of harvested energy, a potential energy can be predicted. When considering an autonomous node with limited resources, the energy predictor must have a low complexity and a small memory space for historical values. Following the comparisons of state-of-the-art energy predictors, including the Exponentially Weighted Moving Average (EWMA) [10], the Weather Condition Moving Average (WCMA) [4] and the Adaptive Filter-based Energy Predictor (AF-EP)[13], AF-EP was selected in this work to meet above requirements. Not only low complexity, independent energy sources and acceptable accuracy (less than 15%), AF-EP also has a small memory space (1 word) as only a previous value of harvested energy is used to estimate the future energy, compared to EWMA (48 words) and WCMA (192 words).

Although EWMA filter is insufficient to predict the harvested energy, it has been shown in [12] that EWMA filter can be used to predict the consumed energy ($\hat{e}_C$) of a WSN node. In [9], 48 words are required to predict the harvested energy profile for 48 slots per day (each slot lasting for 30min). However, our approach only needs to predict the consumed energy in the next slot. Therefore, only one word is used to store the current amount of consumed energy $\tilde{e}_C(n)$ in order to predict the next one $\hat{e}_C(n+1)$. Moreover, activities of the node during a slot are almost the same, especially in monitoring applications, leading to an average value for the consumed energy. In consequence, a moving average using EWMA filter is a suitable choice in this work.

Finally, a power manager (PM) adapts the computation load of the WSN node by determining its wake-up interval (T_{WI}). The PM is implemented by software components and embedded inside the micro-controller of the WSN node. Both energy profiles and energy predictions are taken into account by the PM. As harvested energy is only available during T_{EI} instead of T_{NEI} when considering a periodic energy source, the BQS-PM proposed in this paper has to reserve a part of harvested energy during T_{EI} for continuous powering the node during T_{NEI}. Details of the BQS-PM are given in the next section.

4 BQS-PM: Power Manager with Balanced Quality of Service

Our proposed BQS-PM is composed of two sub-power managers: the Positive and Negative Energy Power Managers (PE-PM and NE-PM). Depending on the amount of harvested power $P_H(n)$, either PE-PM or NE-PM is selected. When $P_H(n)$ is greater than a predefined threshold ε, it means that ambient energy is available and therefore, PE-PM is activated. Otherwise, when there is no more harvested energy ($P_H(n) < \varepsilon$), the second power manager (NE-PM) is used. Both power managers have the dynamic adaptation period $T_S(n)$ proposed in [6], as follows:

$$T_S(n) = kT_{WI}(n) \tag{1}$$

where k is a predefined number of wake-up times in a slot. The value of k is selected in order to trade-off between the reactivities of the PM and its overhead computations.

4.1 Positive Energy Power Manager

Not only adapting wake-up interval of the node according to the current amount of harvested power, the positive energy power manager (PE-PM) has to reserve energy for using afterward. It is obvious that, in average, if the non-harvesting energy interval (T_{NEI}) is φ times longer than harvesting energy interval (T_{EI}), the consumed energy during T_{NEI} is also φ times greater than during T_{EI} in order to achieve the same average performance. Therefore, harvested energy in the next slot $(n+1)$ is divided into $(1+\varphi)$ parts. Only one part is used for operations of the WSN node during slot $(n+1)$ while the remaining harvested energy (φ parts) is reserved in StoreCap. This policy provides us the following constraint:

$$\frac{\hat{P}_H(n+1)T_S(n+1)}{1+\varphi} = \tilde{e}_{Leak}(n+1) + \frac{\hat{e}_C(n+1)}{\eta} \tag{2}$$

where the left hand side is a part of harvested energy during slot $(n+1)$ predicted by the adaptive filter, the right hand side is the total energy consumption including leakage ($\tilde{e}_{Leak}(n+1)$) and energy consumed by the node ($\hat{e}_C(n)$), which is also predicted by using an EWMA filter, and η is the DC/DC converter efficiency. From the results in [12], the leakage energy can be estimated from the leakage power P_{Leak}, which is assumed to be a constant value, as follows:

$$\tilde{e}_{Leak}(n+1) = P_{Leak} T_S(n+1) \tag{3}$$

Meanwhile, the prediction of the energy consumed by the node is:

$$\hat{e}_C(n+1) = (1-\alpha)\tilde{e}_{Active}(n) + \alpha\hat{e}_{Active}(n) + P_{Sleep} T_S(n+1) \tag{4}$$

where α is the weighted factor in the EWMA filter, $\tilde{e}_{Active}(n)$ and $\hat{e}_{Active}(n)$ are the consumed energy of the node and its previous prediction for k wake-up times during slot n, respectively, and $P_{Sleep}T_S(n+1)$ stands for the energy when the node turns into sleep mode. The sleeping time during a slot is approximated as $T_S(n+1)$ (in order of seconds) since the active period is negligible (in order of milli-seconds). It is noticed from (4) that only $\tilde{e}_{Active}(n)$ is used by the EWMA as the node always has k wake-up times within a slot and therefore, the energy consumption is expected an average value. When the node stays in sleep mode, the load current is almost constant, which allows us to estimate energy during the sleep period directly from the sleep power P_{Leak}.

Finally, applying (1), (3), and (4) into (2), we have:

$$T_{WI}(n+1) = \frac{(1+\varphi)\,\hat{e}_{Active}(n+1)/k}{\eta\hat{P}_H(n+1) - (1+\varphi)(\eta P_{Leak} + P_{Sleep})} \tag{5}$$

This result shows the adaptation capability of the autonomous node according to the harvested energy as its next wake-up interval $T_{WI}(n+1)$ is inversely proportional to the harvested power $\hat{P}_H(n+1)$. Moreover, a high value of φ, which means a longer non-harvesting energy interval, produces higher $T_{WI}(n+1)$ for more energy reservation. At the beginning of a new cycle T_C, a Zero Energy Interval predictor (ZEI) proposed in [6] is activate to estimate T_{NEI} and then, φ can be derived. The value of φ can be changed in different conditions. For instance, the light energy occurs almost 12 hours during summer days in our office and therefore, $\varphi \approx 1$. However, during winter days, φ is higher as T_{NEI} provided by the ZEI predictor is longer. All these features are necessary to achieve the same performance during the absence of energy interval with the second power manager, the negative Energy Power Manager (NE-PM), which is presented in the next section.

4.2 Negative Energy Power Manager

When the harvested power $\tilde{P}_H(n)$ is less than a predefined threshold ε, it is considered that there is no more harvested energy. Therefore, operations of the WSN node must rely on energy remaining in StoreCap. Its wake-up interval adaptations during this period are carried out by the Negative Energy Power Manager (NE-PM). In the first step, NE-PM has to estimate the remaining non-harvesting energy interval $R(n+1)$, which is assigned to T_{NEI} when switching from the first power manager (PE-PM) to the second one (NE-PM). $R(n+1)$ is updated at the end of each slot as:

$$R(n+1) = R(n) - T_S(n) \tag{6}$$

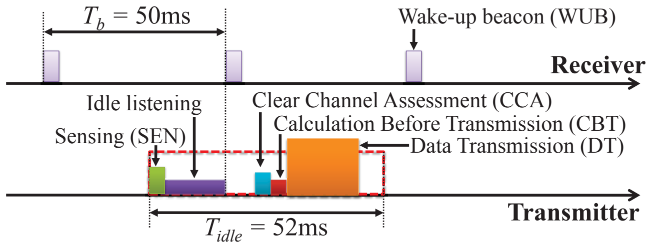

Figure 3. RICER protocol for communications between two nodes.

Then, if the average wake-up interval is $T_{WI}(n+1)$ during $R(n+1)$, the total energy required by the node should be:

$$E_C = \frac{R(n+1)}{T_{WI}(n+1)}\frac{\hat{e}_{Active}(n+1)}{k} + P_{Sleep}R(n+1) \tag{7}$$

where the first term is the energy when the node wakes-up, which is determined from the number of wake-up times $[R(n+1)/T_{WI}(n+1)]$ and the predicted energy for each wake-up $[\hat{e}_{Active}(n+1)/k]$. Meanwhile, the available energy in StoreCap that can be used for powering the node is:

$$E_S = \frac{1}{2}C_S(V_S^2(n) - V_0^2) - P_{Leak}R(n+1) \tag{8}$$

where V_0 is the initial voltage of StoreCap. In order to satisfy the ENO condition, the voltage of StoreCap is expected to be V_0, in other words, all the energy E_C is consumed by the node ($E_C = \eta E_S$) during the non-harvesting energy interval (T_{NEI}). Therefore, the next wake-up interval can be achieved as:

$$T_{WI}(n+1) = \frac{R(n+1)\hat{e}_{Active}(n+1)/k}{\frac{1}{2}\eta C_S(V_S^2(n) - V_0^2) - R(n+1)(P_{Sleep} + \eta P_{Leak})} \tag{9}$$

This result shows that the main goal of the NE-PM is to make the voltage of StoreCap (V_S) converge to its initial value (V_0) at the end of non-harvesting energy interval, to respect the ENO condition. In order to archive the same performance as in the harvesting energy interval, V_S must be less than or equal to V_{Max}, which is the maximum voltage of StoreCap. As soon as $V_S = V_{Max}$, the harvested energy is discarded and average T_{WI} during the absence of energy must be increased to respect the ENO condition. The performance during T_{NEI} is therefore, lower than during T_{EI}. However, increasing StoreCap also increases leakage energy and reduces the global performance. How to choose a good capacitance for StoreCap is discussed in Section 5.

5 Simulation Results

5.1 Simulation Setup on OMNET++

The single-hop network shown in Fig. 1 is implemented on OMNET++ simulator with a base-station (BS) and $N = 3$ end-devices (EDs). Each node is powered by the same harvested energy profile, which is extracted from a real PowWow node[3] powered by two PVs in our office. The energy monitor in [12] is implemented in the PowWow for tracking the amount of harvested power every minute. Communications among EDs and BS are based on the RICER protocol [14] presented in Fig. 3. In this protocol, the receiver sends

Table 1. Performance of BQS-PM with different C_S.

C_S(F)	P_{Leak}(μW)	$\overline{W_{EI}}$(s)	$\overline{W_{NEI}}$(s)	$\overline{W_C}$(s)
0.9	43	18.1	42.9	26.1
1.8	73	21.1	18.9	19.9
2.7	103	25.7	23.0	24.2

a wake-up beacon (WUB) every T_b = 50ms. The transmitter, whenever it wakes-up, creates a packet from the sensing process (SEN) and then, opens an idle listening window to receive a beacon from the receiver. As soon as a WUB is successfully received, it performs Clear Channel Assessment (CCA), Calculation Before Transmission (CBT) and forwards this data packet to the receiver. The maximum idle listening time is set to T_{idle} = 52ms to deal with the clock drift issue. The BQS-PM is implemented in each node with k in (1) set to 10, which is a good trade-off between reactivity and overhead in computations [12][6]. The weighted factor α is assigned to 0.5, which is a common value of an EWMA filter [11]. The threshold ε used to switch between PE-PM and NE-PM is 200μW. The minimum and maximum wake-up intervals are 1s and 300s, respectively. The same StoreCap values are used for all EDs, with minimum and maximum voltage V_{Min} = 1.8V and V_{Max} = 5.2V. At the beginning, the capacitors are charged to V_0 = 2V. Following metrics are used to evaluate the performance of the different PMs:

- $\overline{W_{EI}}$ (s): Average wake-up interval during T_{EI}.
- $\overline{W_{NEI}}$ (s): Average wake-up interval during T_{NEI}.
- $\overline{W_C}$ (s): Average wake-up interval during the whole simulation.
- B_f (min): Battery failure duration, happening when the voltage of StoreCap is less than V_{Min}.

5.2 Sizing of StoreCap

As the role of all three EDs is the same in the single-hop network shown in Fig. 1, ED(1) is chosen for analysis and sizing in the rest of this paper. Three simulations with different capacitance values of StoreCap (C_S) are performed and the results are gathered in Table 1. When C_S = 0.9F, the average wake-up interval when there is harvested energy (T_{EI}) is $\overline{W_{EI}}$ = 18.1s. However, when StoreCap is fully charged, all ambient energy cannot be reserved. Therefore, the wake-up interval when there is no more energy $\overline{W_{NEI}}$ must be reduced to 42.9s in order to satisfy the ENO condition. When C_S is increased to 1.8F or 2.7F, it is sufficient to buffer all harvested energy and the balanced wake-up interval between T_{EI} and T_{NEI} can be achieved. Unfortunately, increasing C_S also increases the leakage power P_{Leak} and reduces the global performance, in other words, the average wake-up interval $\overline{W_C}$ is increased. From results in Table 1, C_S = 1.8F is selected for the following simulations, as this value provides almost the same $\overline{W_{EI}}$ and $\overline{W_{NEI}}$ with the lowest wake-up interval $\overline{W_C}$ = 19.9s.

5.3 Performance Comparisons

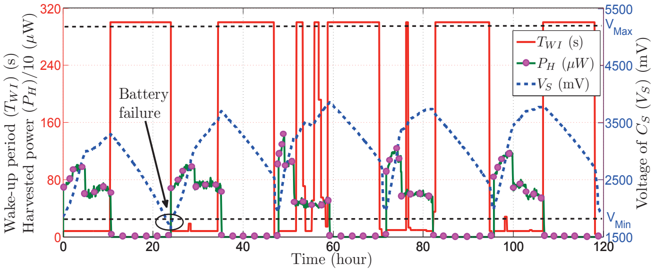

Figure 4. Adaptations of ED(1) using KAN-PM.

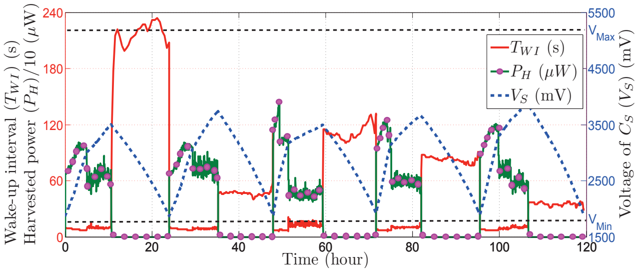

Figure 5. Adaptations of ED(1) using CL-PM.

In the first simulation, KAN-PM is implemented in each ED. Adaptations of ED(1) are shown in Fig. 4 with its wake-up interval (T_{WI}) and voltage of StoreCap (V_S) according to the harvested power (P_H). As it can be observed, T_{WI} often stays at 300s during non-harvesting energy interval (T_{NEI}) but around 9s during harvesting energy interval (T_{EI}). This behavior can be explained by the fact that, based on the total energy that can be harvested (predicted by the EWMA filter), a small part of energy is reserved to guarantee the minimum performance (T_{WI} = 300s) during T_{NEI}, while all remaining energy is used to maximize performance during T_{EI}. Therefore, performance of the node has a high variance between T_{NEI} ($\overline{W_{NEI}}$ = 125.2s) and T_{EI} ($\overline{W_{EI}}$ = 11.1s), which is an issue for monitoring applications. Moreover, T_{WI} is not quickly adapted according to the harvested power (P_H), which can be found at the beginning of the third day. Although the harvested energy is much higher than the second one, the wake-up interval is kept the same as in the second day (T_{WI} = 9s). The surplus energy is used afterward, instead of immediately, to reduce the wake-up interval at the end of the third day. However, the biggest problem of KAN-PM is that battery failure can occur when V_S is less than V_{Min} since V_S, representing the SoC, is not considered in this power manager. As it can be observed from Fig. 4, the node is completely turned off for around B_f = 18 minutes at the end of the first day and turned on again on the second day when harvested energy is available.

Table 2. Performance comparison of different PMs.

	$\overline{W_{EI}}$(s)	$\overline{W_{NEI}}$(s)	$\overline{W_C}$(s)	B_f(min)
BQS-PM	21.1	18.9	19.9	0
KAN-PM	11.1	125.2	20.4	18
CL-PM	10.4	111.6	19.6	0

Then, behaviors of ED(1) when using CL-PM are presented in Fig. 5. The battery failure period is avoided by considering V_S during non-harvesting energy interval. Therefore, operations of the node are kept going on over five days without any interruption. Moreover, V_S is almost around V_0

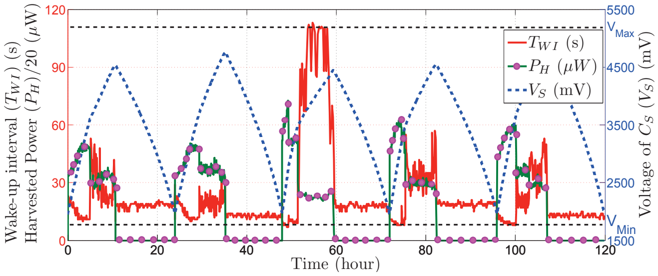

Figure 6. Adaptations of ED(1) using BQS-PM.

at the end of each day, which means the ENO condition is better satisfied than using KAN-PM. However, wake-up interval adaptations when there is ambient energy are extended from an energy neutral power manager, whose objective is to balance consumed energy and harvested energy. The output from this power manager is normalized by a ceil function to provide an integer number. This policy provides a fast adaptation of T_{WI} according to the harvested power but, similar to KAN-PM, the reserved energy is insufficient, leading to a much higher wake-up interval during T_{NEI} compared to T_{EI} ($\overline{W_{NEI}}$ = 111.6s and $\overline{W_{EI}}$ = 10.4s).

By considering the ratio φ between T_{NEI} and T_{NEI}, BQS-PM is able to save plenty of energy to increase the performance during T_{NEI} as shown in Fig. 6. During T_{EI}, whenever the harvested power (P_H) increases, the wake-up interval (T_{WI}) decreases and vice versa, which presents adaptation ability of the WSN node according to P_H. After a day, which is the cycle of the energy source, V_S is recovered closely to $V_0 = 2V$ to satisfy the ENO condition. As the SoC of StoreCap is also taken into account (by NE-PM during T_{NEI}), V_S is always higher than V_{Min} for continuous operation ($B_f = 0$). The significant improvement of BQS-PM compared to related power managers is the performance during T_{NEI}, when there is no harvested energy. As it can be observed from Table 2, average wake-up interval is reduced by 84.89% and 83.07% compared to KAN-PM and CL-PM, respectively. However, BQS-PM does not improve the global performance as after five days, the voltage of V_S is very close to V_0 which means that most of the harvested energy is consumed by the wireless node to maximize the throughput. While BQS-PM balances the total of packets during a whole cycle T_C, KAN-PM and CL-PM send plenty of packets during T_{EI} but very limited amount of packets during T_{NEI}. Therefore, BQS-PM is well adapted for monitoring applications requiring regular data tracking (e.g. monitoring applications).

6 Conclusions

In this paper, a new power manager, named Balanced Quality of Service-based Power Manager (BQS-PM) is proposed for WSNs powered by periodic energy sources. By considering the ratio between non-harvesting and harvesting energy interval (T_{NEI} and T_{EI}), energy can be reserved to achieve the same QoS during the whole cycle of energy sources. This strategy improves the QoS of the WSN node when there is no more harvested energy up to 85% and 83% compared to KAN-PM and CL-PM, respectively. Future work will extend BQS-PM in the context of a multi-hop network, as required for applications in a large area (e.g. big buildings, forest) where a node must forward its packets to a base station through many relay nodes due to the limited radio range.

7 References

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