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Abstract

This paper deals with the medium between two reconfigurable sensor nodes characterized by radio interfaces that support multiple channels for exchanging real-time messages under energy constraints, these constraints are violated if the consumed energy in transmission is higher than the remaining quantity of energy. A reconfiguration, i.e., any addition or removal of tasks in devices and consequently of messages on the medium, can cause the violation of real-time or energy constraints at run-time. To achieve a feasible scheduling in time (i.e., message deadlines will be respected) and energy (i.e., there is available energy) on the medium, we propose new dynamic solutions: Balance, Dilute, and a combination of them to manage any addition or removal of messages. The proposed approach utilizes the energy harvesting techniques and PowerControl algorithm to reduce the non-harvested consumed energy. The proposed strategies achieve significant improvement over existing methods and provide the highest percentage of adding messages, with a lower average in response time and energy consumption. They reach a percentage of success in adding the highest priority messages while meeting deadlines up to 85%.

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***Index Terms*—Energy harvesting, multichannel communication, real-time message, reconfigurable wireless sensor network (RWSN), transmission scheduling.**

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I. Introduction

A WIRELESS sensor network (WSN) is an infrastructure-less wireless network typically composed of energy-constrained sensor nodes running software tasks that exchange messages with remote devices [1], [2]. Traditionally, sensor nodes are powered by batteries with limited capacity which reduces their lifetime. Recently, the development of energy harvesting systems has allowed sensor nodes to benefit from this technology [3], which can be harvested through the use of many techniques, such as photovoltaic (PV) solar energy [4]. One of the major advantages of using energy harvesting is that it is renewable and sustainable so that it will never run out; thus, it is ideal for applications that need to survive for a longer time period. In addition to energy harvesting, the use of multiple channels can significantly increase network capacity, enhance the bandwidth, and reduce delays and, thus, greatly alleviate the drawback of using transmission power to achieve desired communication delays [5], [6].

In most WSN applications, tasks are time and event-critical in the sense that they have strict constraints on the quality of service (QoS) (e.g., delay, packet loss) and energy consumption [7]. These constraints need to be satisfied together with great efficiency and, then, we get more energy savings. Otherwise, we set the priority to satisfy the energy consumption [8]–[11]. The lifetime of WSN is determined by the battery reserves of the sensor nodes composing it. When a sensor node runs with insufficient energy, the QoS degrades and the deadline of messages will not be met [12]–[14]. Due to these constraints, WSN should be highly flexible and reconfigurable so they can adapt their behavior to the environment according to circumstances at run time [15]–[21]. More formally, a WSN is said to be reconfigurable when any modification affects a sensor node at the software or hardware levels [22]–[30].

While there are several reconfiguration options for a reconfigurable WSN (RWSN), we focus this paper on message transmission reconfiguration. We consider the case of the transmission of real-time messages, where each message is periodic and subject to transmission deadlines and energy consumption. In this paper, we show how and when we perform reconfigurations that meet deadlines and energy constraints at run time. In other words, how does a node choose the feasible set of tasks to be executed and messages to be exchanged? What is the message to be added first after any reconfiguration scenario (i.e., after any modification touches sensor nodes on the software or hardware levels)? When does a node need to enable/disable channels in the case, where multiple channels are available for use?

The proposed solution should avoid messages that miss their deadlines or violate the energy constraints of the system. To guarantee the satisfaction of these constraints, we propose new strategies that maintain system feasibility after any reconfiguration scenario, such as modifying message features and adding or removing messages on channels. Our contribution is applied to a case study after we compare the generated results with existing methods to present the originality of the proposed strategies. These strategies achieve significant improvement over existing methods and provide the highest percentage of adding messages according to their priorities, with a low average in response time and energy consumption. Indeed, the proposed strategies focus on making the system feasible in time and energy for adding the maximum possible of messages according to their priorities, which is different from the existing works.

To further reduce energy consumption, we make use of power control and rely on deterministic environmental changes (such as temperature variations) that affect the quality of transmission [31]. Specifically, we provide a feature called PowerControl that allows nodes to use the smallest input current in transmission that is sufficient enough for the transmitted message to reach the destination. Our results prove that PowerControl helps the proposed strategies to achieve a higher success rate of added messages as more energy can be saved (see Section VI for the details).

In addition to power control, we consider a more general case for energy storage and generation, where nodes are also capable of performing energy harvesting to produce more energy. With these features, the main original contribution of this paper is to guarantee real-time messages scheduling in a feasible system in time and energy, and make the non-feasible system feasible by allowing a node at run time to dynamically:

1) perform real-time scheduling in multichannel RWSN under energy harvesting constraints;
2) manage the activation/deactivation of a set of channels in order to meet energy and real-time constraints (Enable/disable channel);
3) adjust message periods and send them over multiple channels (Dilute);
4) divide message traffics on multichannel (Balance);
5) change the period of the lowest priority messages to add the highest ones (Grape);
6) delete the lowest priority messages to add the highest ones (Truncate);
7) save more energy by using the lowest transmission power which relies on deterministic environmental changes, such as temperature variations (PowerControl).

The rest of this paper is organized as follows. Section II summarizes the existing work on real-time WSNs. Section III provides an overview of the contribution. Section IV provides a formal model for multichannel RWSN, including the definitions of system model, energy harvesting, energy storage, and feasibility test. In Section V, we present the main contribution of this paper. Section VI evaluates the performance of the proposed solutions with a case study. Finally, Section VII provides concluding remarks and directions for a future work.

II. Related Work

Most of the research that has been carried out in the context of real-time WSN focuses on finding optimal solutions to guarantee QoS under time and energy constraints.

The works reported in [32]–[34] perform any feasibility test in time under energy harvesting. However, they accept tasks without any priority test, which eliminates the highest priority tasks by lowest priority ones. Also, in [32] and [33], the scheduling is performed without any feasibility test in energy, which leads to wasted energy.

The works reported in [35]–[37] deal with scheduling on multichannels, where there is no guarantee to send the highest priority messages. The work reported in [38] schedules messages according to their priorities on multichannels. The work reported in [39] orders sensor nodes according to the priority of the sent messages. However, the scheduling in the previous works is performed without any feasibility test neither in time nor in energy, which leads to a situation where these constraints are not satisfied.

The works reported in [40] and [41] combine the execution of such periodic and aperiodic real-time tasks. However, the schedule is performed without considering system feasibility in energy. Also, there is no guarantee to send the highest priority messages.

The works reported in [34], [42], and [43] perform time-feasibility tests and energy efficiency. Also, they deal with energy harvesting. However, the scheduling is performed without any feasibility test in energy, which leads to a situation where energy constraints are not satisfied.

The study in [44] deals with messages scheduling based on time-feasibility test. This research work is limited to a situation where real-time data packets have the same deadline, rather than checking system feasibility before adding messages. Thus, it may miss deadlines when real-time data packets have different deadlines. Moreover, the works reported in [45]–[47] perform feasibility tests in energy, but there is no feasibility test in time, implying that there is no guarantee to meet message deadlines.

To the best of our knowledge, no one has considered before the following items together: reconfigurable system, time-feasibility, energy-feasibility, message priorities, multichannel, energy harvesting, and energy efficiency (see Table I). In this paper, we propose a new approach that uses different solutions to handle feasible reconfigurable messages at run time by adjusting their periods and sending them over multiple channels, by dividing their traffic on multichannel and balancing their transmission, by enabling/disabling a set of related channels, by changing the period of the lowest priority messages, or deleting them to add the highest ones. For energy efficiency, we use a new idea for PowerControl based on deterministic environmental changes.

III. Contribution Overview

In this paper, we are interested in adding messages by maintaining the feasibility of the system which is feasible in time and energy if and only if it satisfies real-time and energy constraints of each message, and their transmission can be done normally. Nevertheless, any reconfiguration scenario touches a sensor node at the software or hardware levels, may violate the corresponding constraints. The system is nonfeasible in time or energy, i.e., the channel is saturated or the energy is insufficient, so no more messages can be scheduled and their addition violates transmission deadline or energy consumption. Thus, we apply one of the three proposed strategies: 1) split the worst-case transmission time (WCTT) of the messages over multiple channels which we call the Balance strategy; 2) increase the message periods to send them over several channels which we call the Dilute strategy, change message periods given in several recent work as in [48]–[50]; or 3) the combination of both, by choosing in each time the strategy that gives solutions with higher required QoS. If the system is still nonfeasible in time or energy after applying one of the proposed strategies, then it chooses one of the following technical solutions: 1) enable a new channel if it is not feasible in time; 2) disable a channel if it is not feasible in energy; 3) increase message periods with the lowest priority to add messages with higher priority; or 4) delete messages with lower priority to add other higher priority messages if it is not feasible in time or energy. If the system is feasible in time and energy, then it will use the earliest deadline first (EDF) scheduling algorithm for messages transmission. The EDF scheduling algorithm was used recently in real-time WSNs applications, where it has been found to be an effective transmission scheduling policy for real-time WSANs in [51]. It is also an optimal scheduling algorithm without preemption costs [52], and as given in [53], the scheduling of real-time messages according to EDF guarantees bounded delay of messages and makes use of all available bandwidth of wireless medium.

IV. Formalization of Multichannel RWSN

In this section, we formally describe the system model of RWSN, and give mathematical representations of its time and energy constraints.

A. System Model

We consider an RWSN composed of reconfigurable nodes communicating via radio interfaces and powered by batteries that can be recharged with energy harvesting. In RWSN, each reconfigurable node has a set of tasks. A task can consist, for example, in the transmission of a periodic message. We consider the case where a node has multiple radio interfaces that allow simultaneous parallel transmissions over a set of channels $\mathcal{C}$. For the sake of simplicity, we assume that these channels have the same gain and, thus, each channel has the same transmission speed as the others. We use B (bits/s) to refer to such transmission speeds. For the modeling of energy consumption, we consider that the node radio interface can be in one of the following three modes: 1) transmission; 2) reception; and 3) idle. We denote P_{tx} (resp. P_{rx} and P_{idle}) as the power consumption in transmission (resp. reception and idle) mode during a time interval T_{tx} (resp. T_{rx} and T_{idle}). The idle mode is when the node is neither performing transmission nor reception. Pt_τ (resp. Ps_τ) is the transmission power (resp. the reception sensitivity) under temperature τ.

Let $\mathcal{M}$ be the set of messages that are planned to be transmitted. We use $\mathcal{M}_s^j$ (resp. $\mathcal{M}_s^{\mathcal{C}}$) to refer to the messages that are already being transmitted over channel c_j (resp. set of channels $\mathcal{C}$). We use $\mathcal{M}_{\bar{s}}^{\mathcal{C}}$ to refer to the messages that have been removed from all channels $\mathcal{C}$, due to the arrival of messages with higher priorities. We use m_i to refer to the new periodic message ($m_i \in \mathcal{M}, i = 1 \dots |\mathcal{M}|$), which is considered for addition subject to the satisfaction of both time and energy constraints. Message m_i has the following characteristics according to model of Liu and Layland.

1) An arrival time r_i.
2) A periodicity T_i that is the interval between two consecutive message arrivals.
3) A soft deadline interval D_i[1] within which the message should be completely transmitted from its r_i until it is completely received by the destination, i.e., the last bit of the message should reach the destination before $r_i + D_i$. We consider that the soft deadline interval for m_i is equal to the message arrival period, i.e., $D_i = T_i$.
4) A hard deadline interval $D\max_i$ within which the message must be completely transmitted; otherwise the message is considered as not feasible (see [54] for an example on soft and hard deadlines).
5) A WCTT and worst-case energy consumption (WCEC), such as $\text{WCTT}_{i,j}$ (resp. $\text{WCEC}_{i,j}$) refers to the WCTT (resp. WCEC) of m_i over channel c_j, which is the ratio between the size of a message and the transmission speed of a channel, i.e., $(|m_i|/B)$.
6) A priority, where each flow of messages (i.e., a sequence of messages that are produced/transmitted continuously in each time period) may have a different priority than other flows (note that the priority of a flow may change over time under environmental circumstances).
7) A density, denoted as σ_i, representing the number of message instances that should be sent in time interval.
8) A response time, $\mathcal{RT}_i$, defined as the time elapsed from the arrival time r_i until the entire reception of the message by the destination node.
9) A QoS that depends on many parameters, such as the response time of message m_i.

[1]Note that the concept of soft deadline means that it is preferred that the message be transmitted within this interval, but there are no serious consequences if that deadline cannot be met.

TABLE I
COMPARISON OF THE RELATED WORK (E. HARV.: ENERGY HARVESTING, T.-FEAS.: TIME-FEASIBILITY, E.-FEAS.: ENERGY-FEASIBILITY, PR. MSG: PRIORITY MESSAGES, AND E. EFFI.: ENERGY EFFICIENCY)

Strategy	**Reconfiguration**	**Multi-channel**	**E. Harv.**	**Split WCTT**	**Change Period**	**T.-Feas.**	**E.-Feas.**	**Pr. Msg.**	**E. Effi.**	**Key features: + advantages, - limitation**
[39]	No	Yes	No	No	No	No	No	Yes	No	+ Gives more opportunities and channels to the highest priority messages. - No guarantee in system feasibility neither in time nor energy.
[38]	No	No	No	No	No	No	No	Yes	No	+ Schedule messages based on their priorities. - No guarantee in system feasibility neither in time nor energy.
[35], [37]	No	Yes	No	No	No	No	No	No	No	+ Use multi-channel to send multiple packets simultaneously. - No guarantee in system feasibility neither in time nor energy. - No guarantee to send the highest priority messages.
[36], [40], [41], [44]	No	No	No	No	No	Yes	No	No	No	+ Using FCFS or RM makes the transmission simple and easy. + [40], [41], are interesting in aperiodic messages scheduling. - No guarantee in system feasibility in energy. - No guarantee to send the highest priority messages. - [36], [44], are Limited to a situation where messages have the same deadline.
[45]	No	No	No	No	No	No	Yes	No	No	+ Adapting messages scheduling with energy consumption. - No guarantee in system feasibility in time. - No guarantee to send the highest priority messages.
[32], [33]	Yes	No	Yes	No	No	Yes	Yes	No	No	+ System feasibility in time and energy is guaranteed during messages transmission. - No guarantee to send the highest priority messages. - No energy saving in the absence of energy harvesting.
[42], [43]	No	No	No	No	No	Yes	No	No	Yes	+ System feasibility in time is guaranteed during messages transmission. - No guarantee in system feasibility in energy. - No guarantee to send the highest priority messages.
[34]	No	No	Yes	No	No	Yes	No	No	Yes	+ System feasibility in time is guaranteed during messages transmission. + Energy saving in the absence of energy harvesting. - No guarantee in system feasibility in energy during messages transmission. - No guarantee to send the highest priority messages.
[46]	No	No	Yes	No	No	No	No	No	No	+ Messages scheduling under energy harvesting. - No guarantee in system feasibility neither in time nor energy during messages transmission. - There is no energy saving in the absence of energy harvesting. - No guarantee to send the highest priority messages.
[47]	No	No	No	No	No	No	Yes	No	Yes	+ Messages transmission under energy management. - No guarantee in system feasibility in time during messages transmission. - No guarantee to send the highest priority messages.
The proposed Strategies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	+ Handle feasible reconfigurable messages at run-time by adjusting their periods or dividing their traffic on multi-channel. + Maximize system capacity by using simultaneous parallel transmissions over mutliple channels. + System feasibility in time and energy is guaranteed during messages transmission. + Schedule messages based on their priorities, with guarantee to send the highest priority. + Messages scheduling under energy harvesting. + Energy saving in the absence of energy harvesting. - Lower priority messages have fewer transmission opportunities than others.

In this paper, we focus on periodic tasks since aperiodic ones can be managed by using periodic servers [55], where we are providing guarantees that the system is feasible and scheduled even in the worst-case situations; thus, we are considering the case when messages use their WCTT exactly.

B. Time Feasibility

We say that a system is time-feasible if and only if it can meet related real-time constraints [32]. Thus, for checking the system feasibility, we consider the case where the scheduling of real-time messages is made according to the EDF, i.e., the incoming real-time traffic is served in deadline order to guarantee the WCTT (see [56]). When a node checks the time feasibility of accepting a new message, it uses the EDF algorithm for a required feasibility test. The basic algorithm reported in [57] can be used for the scheduling of real-time traffic of message m_i over a given channel when the period is equal to the deadline, i.e., $T_i = D_i$. To make sure that all deadlines of message m_i transmitted over channel c_j are met, the use of real-time traffic must not exceed the total utilization factor U_j of channel c_j. The maximum theoretical utilization U_j is equal to 1, i.e., the utilization of the channel is 100%. The system is time-feasible to send the set of messages $\mathcal{M}_s^j$ over channel c_j if these messages are sent without exceeding their deadlines at each period according to the EDF algorithm. Thus, the total channel utilization is defined according to the EDH scheduling algorithm as given in [57]

$$U_j = \sum_{i=1}^{|\mathcal{M}_s^j|} \frac{\mathrm{WCTT}_{i,j}}{T_i} \leq 1. \tag{1}$$

C. Energy Feasibility

A sensor node has two types of energy: 1) energy harvesting and 2) storage, which represents a strict constraint that must be respected. Therefore, the system is energy-feasible if and only if it can meet energy constraint [32], where it is violated if the energy consumed in transmitting a message is higher than its remaining energy.

1) Energy Harvesting: We suppose that the amount of energy that can be harvested, referred as E_H, is collected from a PV power source (i.e., solar energy). The output power $P_{\mathrm{PV}}(t)$ of PV generator at particular time t is given according to [58] by

$$P_{\mathrm{PV}}(t) = \eta(t) \times N \times A \times G \tag{2}$$

where $\eta(t)$ is the instantaneous PV generator efficiency at particular time t; N is the number of modules in the PV generator; A is the area of signal module used in system (measured in m^2); and G is the global irradiation incident on the titled plane (measured in W/m^2).

Let $E_H([t_1, t_2])$ be the total energy produced during time interval $[t_1, t_2]$ by the PV power source $P_{\mathrm{PV}}(t)$. We assume that t_2 and t_1 are integer time units. According to [32] and by supposing that the energy is harvested uniformly over this time interval, we have

$$E_H([t_1, t_2]) = \int_{t=t_1}^{t_2} P_{\mathrm{PV}}(t)dt. \tag{3}$$

2) Energy Storage: The sensor node has only one energy storage unit, usually a battery, which has a nominal capacity expressed in units of energy. The residual battery capacity at time t is $C_B(t)$, which is the remaining energy in the battery. The energy that will be consumed by the forthcoming messages after time t may be higher than the residual battery capacity $C_B(t)$. The battery is considered to be fully discharged if its residual capacity $C_B(t) \approx 0$.

3) Energy Consumption: We suppose that nodes consume most of their energy resources in communication [59] and thus focus on the consumed energy during communication. The amount of consumed energy per node in communication is equal to the sum of the consumed energy by its radio circuitry in each of the following modes: transmission, reception, and idle as reported in [60]. In this paper, we focus on the consumed energy by the transmitting node. Note that for the transmission of a message, the radio circuitry needs to switch to idle mode before going to transmission mode to send messages. Therefore, the consumed energy E_j for a transmission of one single message m_i ($m_i \in \mathcal{M}_s^j$) on a given channel c_j ($c_j \in \mathcal{C}$) is given by

$$E_j = P_{\mathrm{tx}} T_{\mathrm{tx}} + P_{\mathrm{idle}} T_{\mathrm{idle}}. \tag{4}$$

The $\mathrm{WCTT}_{i,j}$ of this message is related to its transmission time T_{tx}. When the message is transmitted over a single channel c_j, $\mathrm{WCTT}_{i,j}$ equals to its transmission time. However, in the case where the $\mathrm{WCTT}_{i,j}$ is to be divided into different WCTTs, the message is transmitted on different channels, and each WCTT is processed separately. Therefore, the amount of consumed energy in the transmission on channel c_j for message m_i over a period of time $[t_1, t_2]$ is given by

$$E_j([t_1, t_2]) = \sum_{i=1}^{|\mathcal{M}_s^j|} \left(P_{\mathrm{tx}} \mathrm{WCTT}_{i,j} + P_{\mathrm{idle}} T_{\mathrm{idle}}\right) \left\lceil \frac{t_2 - t_1}{T_i} \right\rceil. \tag{5}$$

Let P_{tx}, P_{idle}, and T_{idle} have a constant value in the time interval $[t_1, t_2]$. By using (1) and (5), the consumed energy by channel c_j can be written with two constants C_1 and C_2 as follows:

$$E_j([t_1, t_2]) = U_j P_{\mathrm{tx}}(t_2 - t_1) + \sum_{i=1}^{|\mathcal{M}_s^j|} \frac{1}{T_i} P_{\mathrm{idle}} T_{\mathrm{idle}}(t_2 - t_1) \tag{6}$$

$$= U_j C_1 + \sum_{i=1}^{|\mathcal{M}_s^j|} \frac{1}{T_i} C_2. \tag{7}$$

The system is energy-feasible (i.e., there is an available energy) in the time interval $[t_1, t_2]$ if

$$\sum_{j=1}^{|\mathcal{C}|} E_j([t_1, t_2]) < C_B(t_1) + E_H([t_1, t_2]). \tag{8}$$

V. Adaptive Multichannel RWSNs Under RealTime and Energy Constraints

We propose an approach for multichannel RWSN under real-time and energy constraints. The key idea behind the proposed strategies is to allow all messages to meet their deadlines according to their priorities by making the system feasible in time and energy. To meet the energy feasibility constraint, we rely on the prevision of the energy that will be available for a predefined time interval in the future.

A. Motivation

As described in the flowchart presented in Fig. 1, when new message m_i arrives, the node starts by checking system feasibility to add m_i in a single channel. If it is time-feasible and energy-feasible, then m_i will be sent over this channel. Otherwise, the node uses the Balance or Dilute strategy which

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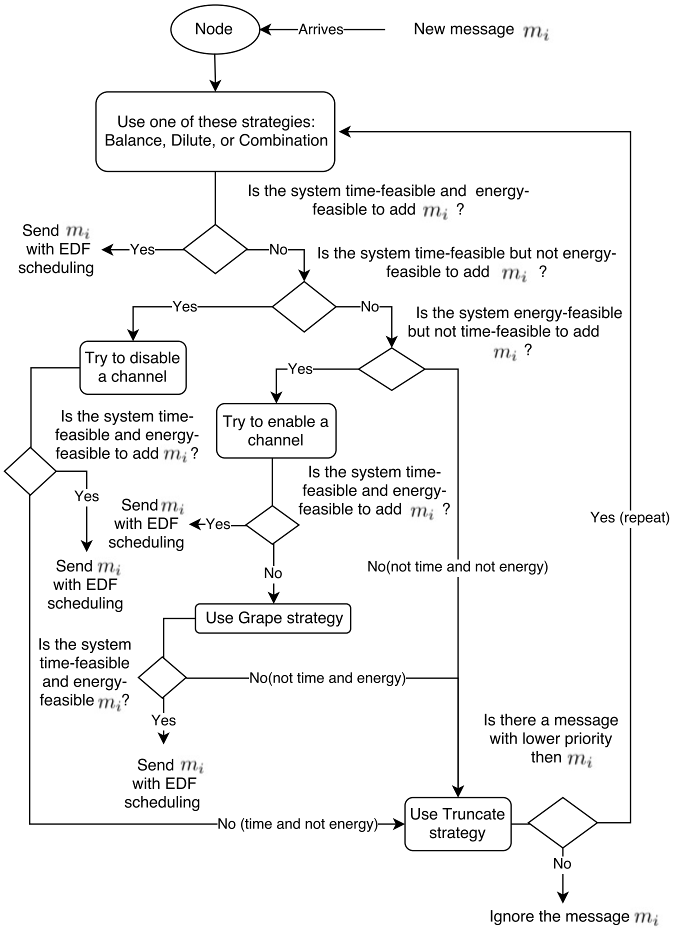

Fig. 1. Message scheduling global strategy for real-time RWSN under time and energy constraints.

makes it feasible in time and energy to add m_i, and provide the best transmission strategy that minimizes the response time of the message $\mathcal{RT}_i$. If the system is time-feasible and energy-feasible, then the message is sent according to the EDF scheduling algorithm.

However, if the system is time-feasible and not energy-feasible to add message m_i, then we attempt to disable a channel that is used for the transmission of messages that have a lower priority than m_i. If after disabling a channel we get energy and time feasibility to transmit m_i then this channel is disabled.

In the case, where the system is only energy-feasible but not time-feasible, we attempt to enable a channel. If the enabling of the channel allows the feasibility in time and energy, then the message is transmitted over the newly enabled channel. If no such a channel can be identified, then we use the Grape strategy that consists in identifying the lowest priority message and lowering its transmission periodicity. If the lowest priority message is identified then its transmission periodicity is lowered and message m_i is added.

In the case, where the system is not time-feasible nor energy-feasible to add m_i, we attempt to use the Truncate strategy which identifies and deletes messages with lower priority than m_i. If these messages are identified, then they are deleted and the nodes restart again with Balance/Dilute as shown in Fig. 1. Otherwise, the system will not be feasible in time nor energy for adding message m_i, thus the message will be ignored.

B. Balance Strategy

In the Balance strategy, when the system becomes nonfeasible in time or energy after adding message m_i, we attempt to split the WCTT of this message into different WCTT generated from a set of available channels referred to $\mathcal{C}_a$. In other words, each channel says how much bits from m_i can be sent according to T_i and its B_j. Each channel c_j gives $\text{WCTT}_{g,j}$ for m_i as follows:

$$\text{WCTT}_{g,j} = \left(1 - \sum_{k=1}^{|\mathcal{M}_s^j|} \frac{\text{WCTT}_{k,j}}{T_k}\right) \times T_i \qquad \forall c_j \in \mathcal{C}_a.$$

If channel c_j gives $\text{WCTT}_{g,j}$ sufficient to send m_i, i.e., $\text{WCTT}_{g,j} \geq \text{WCTT}_{i,j}$, then m_i will be sent over this channel with its $\text{WCTT}_{i,j}$. Otherwise, m_i will be assigned to C_a according to the rest of its WCTT. For example, if it is assigned to channel c_j with $\text{WCTT}_{g,j}$ ($\text{WCTT}_{g,j} < \text{WCTT}_{i,j}$), then it will be assigned to another channel by the rest of its WCTT, i.e., with $\text{WCTT}_{i,j} - \text{WCTT}_{g,j}$, and so on, until satisfying the following:

$$\sum_{j=1}^{|\mathcal{C}_a|} \text{WCTT}_{g,j} \times B_j \geq |m_i|. \tag{9}$$

Thus, the system is time-feasible and energy-feasible if it satisfies the following equations:

$$\begin{cases} \text{WCTT}_{g,j} = \left(1 - \sum_{k=1}^{|\mathcal{M}_s^j|} \frac{\text{WCTT}_{k,j}}{T_k}\right) \times T_i \qquad \forall c_j \in \mathcal{C}_a \\ \sum_{j=1}^{|\mathcal{C}_a|} \text{WCTT}_{g,j} \times B_j \geq |m_i| \\ \sum_{j=1}^{|\mathcal{C}|} E_j([t_1, t_2]) < C_B(t_1) + E_H([t_1, t_2]). \end{cases} \tag{10}$$

In each round of the Balance algorithm (see Algorithm 1), the node tries to send messages by splitting their WCTT and balancing the transmission of them over a set of channels. Otherwise, it uses the technical solutions that will be described below, as given in Fig. 1.

C. Dilute Strategy

In the Dilute strategy, when the system becomes nonfeasible in time or energy after adding message m_i ($m_i \in \mathcal{M}$), this message will have its period T_i lengthened and becomes $T\text{new}_i$ in addition to its transmission being spread over several channels so as to make the system time-feasible and energy-feasible over the set of available channels $\mathcal{C}_a$. We have

$$\sum_{k=1}^{|\mathcal{M}_s^j|} \frac{\text{WCTT}_{k,j}}{T_k} + \frac{\text{WCTT}_{i,j}}{T\text{new}_i} \leq 1 \qquad \forall c_j \in \mathcal{C}_a. \tag{11}$$

As a result, the new period $T\text{new}_i$ which will be assigned to message m_i is the multiplication of the available channels number which is referred as $\mathcal{C}_n$ by the initial period T_i of

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

Algorithm 1: Balance Strategy

Input: m_i: Periodic message
Output: $\mathcal{C}_a$: Available Channel Set
/* Divide the WCTT of message m_i over channels */
if $\exists \mathcal{C}_a \in \mathcal{C}$ *that satisfies the set of equations* (10) **then**
  m_i is balanced over these channels;
else
  if *System is time-feasible but not energy-feasible* **then**
    DisableChannel();
  else
    if *System is energy-feasible but not time-feasible* **then**
      /* Attempt to enable a channel */
      if *There is channel* c_j *that is disabled* **then**
        Enable(c_j);
        $\mathcal{C}_a \cup \{c_j\}$;
      else
        /* All channels are already enabled */
        Grape();
      end
    end
  end
  if *System is not time-feasible or not energy-feasible* **then**
    /* There is message m_l with a lower priority than m_i */
    if $\exists m_l \in \mathcal{M}_s^{\mathcal{C}},\ m_l.priority < m_i.priority$ **then**
      /* Delete this message m_l */
      Truncate(m_l);
      Balance(m_i);
    end
  end
end
/* Transmit message m_i with $WCTT_{i,j}$ over the set of channels $\mathcal{C}_a$ according to EDF scheduling algorithm. */
Transmit(m_i, $\mathcal{C}_a$, $WCTT_{i,j}$, EDF);

Algorithm 2: Dilute Strategy

Input: m_i: Periodic message
Output: $\mathcal{C}_a$: Available Channel Set
/* Dilute message m_i by lengthening its period over channels */
if $\exists \mathcal{C}_a \in \mathcal{C}$ *that satisfies the set of equations* (13) **then**
  m_i is diluted over these channels with $Tnew_i$;
else
  if *System is time-feasible but not energy-feasible* **then**
    DisableChannel();
  else
    if *System is energy-feasible but not time-feasible* **then**
      /* Attempt to enable a channel */
      if *There is channel* c_j *that is disabled* **then**
        Enable(c_j);
        $\mathcal{C}_a \cup \{c_j\}$;
      else
        /* All channels are already enabled */
        Grape();
      end
    end
  end
  if *System is not time-feasible or not energy-feasible* **then**
    /* There is message m_l with a lower priority than m_i */
    if $\exists m_l \in \mathcal{M}_s^{\mathcal{C}},\ m_l.priority < m_i.priority$ **then**
      Truncate(m_l);
      Dilute(m_i);
    end
  end
end
/* Transmit message m_i with $WCTT_{i,j}$ over the set of channels $\mathcal{C}_a$ according to EDF scheduling algorithm. */
Transmit(m_i, $\mathcal{C}_a$, $WCTT_{i,j}$, EDF);

message m_i, with a condition that the new period $T\text{new}_i$ does not exceed the maximum deadline $D\text{max}_i$. Thus, we have

$$T\text{new}_i = (\mathcal{C}_n \times T_i) \leq D\text{max}_i. \tag{12}$$

Then, arrival time r_i has to be incremented by initial period T_i and thus is equal to r_i for the first channel, and to $r_i + T_i$ for the second one, and so on.

System is time-feasible and energy-feasible over $\mathcal{C}_a$ if it satisfies the following equations:

$$\begin{cases} \sum_{k=1}^{|\mathcal{M}_s^i|} \frac{\text{WCTT}_{k,j}}{T_k} + \frac{\text{WCTT}_{i,j}}{T\text{new}_i} \leq 1 \qquad \forall c_j \in \mathcal{C}_a \\ \sum_{j=1}^{|\mathcal{C}|} E_j([t_1, t_2]) < C_B(t_1) + E_H([t_1, t_2]) \\ T\text{new}_i = (\mathcal{C}_n \times T_i) \leq D\text{max}_i \\ 1 \leq \mathcal{C}_n \leq |\mathcal{C}|. \end{cases} \tag{13}$$

In each round of the Dilute algorithm (Algorithm 2), the node calculates for each channel the minimum period $T\text{new}_i$ which makes the system time-feasible with the message m_i, where $T\text{new}_i = \mathcal{C}_n \times T_i$. Next, the node finds a minimum $T\text{new}_i$ which means finding the minimum $\mathcal{C}_n$.

In the case where this strategy cannot be applied, the node uses the technical solutions described below, as given in Fig. 1. To take the advantage of both Balance/Dilute and to increase the percentage of adding messages, we propose to use the combination of both Balance and Dilute strategies (see Fig. 1).

D. Combination of Balance and Dilute Strategies

In the combination strategy, we analyze the case when the node combines the use of Balance and Dilute strategies for adding a message. The node chooses the strategy that can add this message, and if both strategies can add the same message,

Algorithm 3: Disable Channel

Input: m_i

/* Disable a channel whose utilization U_j satisfies the following conditions */

for each $c_j \in \mathcal{C} \setminus \mathcal{C}_a$ **do**

if $\forall m_k \in \mathcal{M}_s^j,\ m_k.priority < m_i.priority$ ***and*** $\sum_{h=1,h\neq j}^{|\mathcal{C}|} E_h([t_1,t_2]) < C_B(t_1) + E_H([t_1,t_2])$ **then**

  Disable(c_j);

end

Algorithm 4: Grape Strategy

Input: m_i: Periodic message

Output: $\mathcal{C}_a$: Available Channel Set

/* Change the period of a message with lower priority than m_i */

if $\exists c_j \in \mathcal{C}, \exists m_l \in \mathcal{M}_s^j,\ m_l.priority < m_i.priority$ ***and*** *the new period of* m_l *satisfies the set of equations* (14) **then**

  $$T_l \leftarrow \frac{WCTT_{l,j}}{1-\left(\sum_{k=1}^{|\mathcal{M}_s^j \setminus \{m_l\}|} \frac{WCTT_{k,j}}{T_k} + \frac{WCTT_{i,j}}{T_i}\right)};$$

  $\mathcal{C}_a \cup \{c_j\}$;

end

then we choose the one which gives the lower response time with this message.

If the system is time-feasible and energy-feasible, then we use EDF scheduling algorithm for transmission. Otherwise, we use one of the following technical solutions as described in Fig. 1.

1) Enabling/Disabling Channel: When system is energy-feasible but not time-feasible after adding message m_i, we need to enable another channel to send this message under the related real-time constraint. However, if the system is time-feasible but not energy-feasible, then we attempt to disable channel c_j such that: 1) the set of messages $\mathcal{M}_s^j$ on that channel have lower priority than new message m_i and 2) when we disable this channel, the system becomes energy-feasible (i.e., $m_i \in \mathcal{M}_s^{\mathcal{C}_a}$, Fig. 1). This strategy is described in Algorithm 3.

When the system is not time-feasible and there is no channel that can be enabled, we use Grape strategy as in Fig. 1.

2) Grape Strategy: We propose to increase the period of message $m_l \in \mathcal{M}_s^j$ with the lowest priority over channel c_j, so that the system becomes time-feasible and energy-feasible to transmit this message over channel c_j as described in Algorithm 4.

The message m_i can be scheduled if the new period of message m_l satisfies

$$\begin{cases} T_l = \dfrac{\mathrm{WCTT}_{l,j}}{1-\left(\sum_{k=1}^{|\mathcal{M}_s^j \setminus \{m_l\}|} \frac{\mathrm{WCTT}_{k,j}}{T_k} + \frac{\mathrm{WCTT}_{i,j}}{T_i}\right)} \\ \text{with,} \quad \left(\sum_{k=1}^{|\mathcal{M}_s^j \setminus \{m_l\}|} \frac{\mathrm{WCTT}_{k,j}}{T_k} + \frac{\mathrm{WCTT}_{i,j}}{T_i}\right) < 1 \\ T_l \leq D\mathrm{max}_l. \end{cases} \tag{14}$$

If the system is not time-feasible or is not energy-feasible, then the node uses Truncate strategy to filter messages according to their priorities as shown in Fig. 1.

3) Truncate Strategy: In this part, when the system is not time-feasible or is not energy-feasible for adding message m_i, we look for message m_l or a set of messages $\mathcal{M}_{\bar{s}}^{\mathcal{C}}$ with a lower priority than message m_i. After deleting them, the system will be time-feasible and energy-feasible for adding m_i.

4) PowerControl: The key idea consists in using the lowest transmission power that guarantees the connectivity of the network. According to [31], the communication range R varies according to temperature variations τ, which has an effect on the transmission power Pt and reception sensitivity Ps. And assuming the following heuristics: the smallest input current that maintains the correct operation of the network will achieve the lowest energy consumption, the transmission power Pt, the input current I, and R are linked together according to the transmission range equation [as coming in [31] and (15)]. Thus, finding the lowest Pt means finding the smallest input current I^* and the shortest R, where I^* is the current required to reach the destination node at distance d (under this assumption, d is the shortest transmission range). Thus, by replacing R by d, and replacing Ps by the reception power Pr in [20], we obtain the smallest input current I^* that achieves the lowest energy consumption. Consequently, the lowest transmission power $\mathrm{Pt}_\tau(I^*)$ at temperature τ is given by

$$d = 10^{((\mathrm{Pt}_\tau(I^*) - \mathrm{Pr}_\tau - A_0)/(10\alpha))} \tag{15}$$

with

$$\mathrm{Pt}_\tau\left(I^*\right) = 10\alpha \log_{10}(d) + \mathrm{Pr}_\tau + A_0. \tag{16}$$

By using a linear approximation to interpolate the provided values in the *Data Sheet* of a widely used radio chip 2400, we obtain the values of I^* corresponding to d. Thus, the power consumed in transmission $P_{\mathrm{tx}}(I^*)$ is given by

$$P_{\mathrm{tx}} = I^* V \tag{17}$$

where V is the radio circuitry tension measured in volts. This technical solution is used by a node to save energy during transmission.

E. Complexity Study

To assess the complexity of the proposed contribution, we use n to refer to the number of channels, i.e., $n = |\mathcal{C}|$ and m to refer to the number of messages that are planned to be transmitted, i.e., $m = |\mathcal{M}|$. Balance and Dilute algorithms require a complexity of $O(1)$ in the best case, i.e., when the system is time-feasible and energy-feasible. Otherwise, if the system is not time-feasible or is not energy-feasible and the system uses Truncate, then the complexity of the proposed strategies becomes $O(n \times m)$, which is the number of iterations that are needed in the worst case.

TABLE II
EXAMPLE FOR THE ADDITION OF A SET OF MESSAGES

Message	ReleaseTime	WCTT	Period	Priority	Dmax
m_1	t_0	70	300	2	600
m_2	t_1	80	100	8	200
m_3	t_2	40	200	3	400
m_4	t_3	60	600	4	1200
m_5	t_4	50	350	5	700
m_6	t_5	40	550	5	1100
m_7	t_6	60	100	7	200
m_8	t_7	50	200	4	400
m_9	t_8	80	200	9	400

VI. EXPERIMENTATION

A. Application

We consider a reconfiguration scenario in which a set of messages is added over two channels: Channel$_1$ and Channel$_2$. Messages are characterized by their: arrival time, WCTT, period, priority, and maximum deadline, as shown in Table II, and are added according to the description presented in Table III. The addition of these messages is performed according to the strategies that we propose in Section V.

B. Evaluation

In order to evaluate the impact of the proposed strategies on deadline success, we measure the percentage of successfully added messages, i.e., those messages that have been added according to their priorities while ensuring that the system is time-feasible and energy-feasible. We evaluate the performance of the three proposed strategies: 1) Balance; 2) Dilute; and 3) Combination for adding more than 300 random messages and 100 aperiodic ones, and compare them with related strategies, such as EDH [32], DMP [37], RTQS [38], DPSC_PR/DPSC_FR [40], and GlobalScheduler [41] (a sample of the proposed experiment with comparative videos is given in).[2]

These works are chosen because they are the closest to our proposal, where:

1) related works that deal with energy harvesting and real-time scheduling:
   a) *EDH* adds periodic messages after performing feasibility test in time and energy, then schedules them according to EDF under energy harvesting constraints;
2) related works that deal with multichannel and real-time scheduling:
   a) *DMP* adds periodic messages over multiple channels, then schedules them according to FCFS;
3) related works that deal with message priorities and real-time scheduling:
   a) *RTQS* adds periodic messages based on their priorities, then schedules them according to FCFS;
4) related works that deal with real-time scheduling of periodic and aperiodic messages:
   a) *DPSC_PR/DPSC_FR* adds periodic messages under offline feasibility test in time and aperiodic messages in the available slack time, i.e., online feasibility test in time, then schedules them according to EDF;
   b) *GlobalScheduler* adds periodic messages under feasibility test in time and aperiodic messages in the available slack time, then schedules them according to rate monotonic (RM).

[2] Y. B. Aissa, A. Bachir, M. Khalgui, A. Koubaa, Z. Li, and T. Qu, "On feasibility of multichannel RWSNs under real-time and energy constraints," https://yousrabenaissa92.wixsite.com/reconfigurablewsn, 2018, accessed: 2019-01-22.

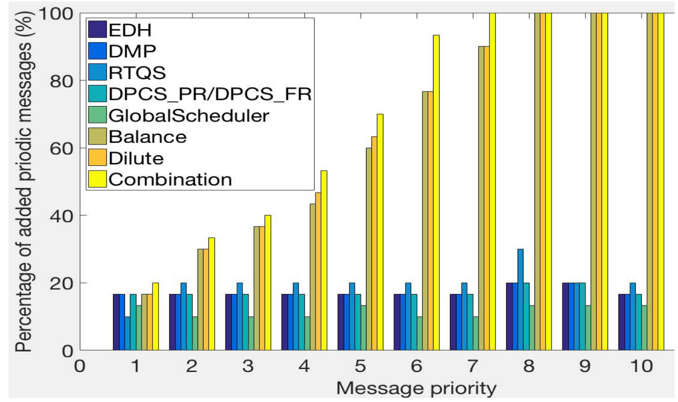

Fig. 2. Percentage of priority messages transmitted according to their priority over multichannel (with 3 channels).

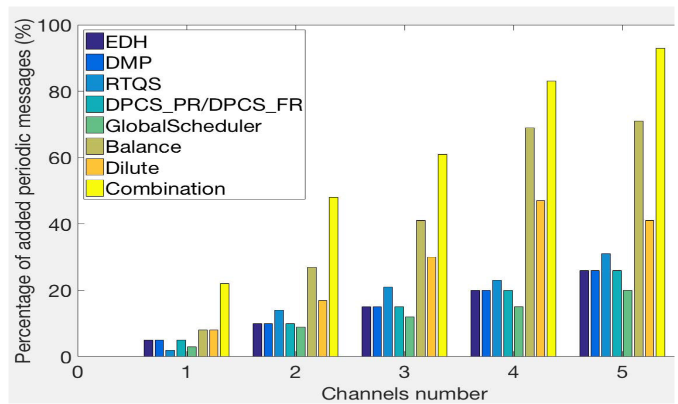

Fig. 3. Percentage of periodic messages transmitted over multichannel.

In the previous works, we note that there is no solution to make the nonfeasible system feasible in time and energy, there is no guarantee to send the high priority messages, also we note in some works that there is no guarantee to meet message deadlines and energy constraints.

To evaluate the effect of managing the list of active channels in this case study on the performance of adding messages according to their priorities, a set of periodic messages is coming with the same WCTT and random period and priority (priorities between 1 and 10), while messages are added sequentially according to their arrival time. Then, we run a series of simulation by varying the number of channels and plot the message addition success rates in Fig. 2. The results shown in this figure are as follows.

1) The message addition success rates achieved by the proposed strategies: Dilute, Balance, and Combination

TABLE III
SEQUENCE OF RECONFIGURATION SCENARIOS AND APPLICATION OF THE PROPOSED STRATEGY

Reconfiguration scenario	Channel Utilization		Average Response Time		Average Energy Consumption		Messages	Interpretations
	$Channel_1$	$Channel_2$	$Channel_1$	$Channel_2$	$Channel_1$	$Channel_2$		
during $[t_0, t_5]$ run: Enable Channel	$U_1 = 0.55$	$U_2 = 1$	142.5	135	$0.55C_1 + 0.00968C_2$	$C_1 + 0.015C_2$	$\mathcal{M}_s^1 = \{m_1, m_4, m_5, m_6\}$ $\mathcal{M}_s^2 = \{m_2, m_3\}$	The system is time-feasible and energy-feasible for adding m_1 on $Channel_1$, so m_1 is added without any reconfiguration. The system is not time-feasible to add m_2 on $Channel_1$. Thus, the system enables new channel $Channel_2$ where message m_2 will be sent over this channel. The system is time-feasible and energy-feasible to send m_3, m_4, m_5, and m_6 over both channels $Channel_1$ and $Channel_2$.
In t_6 run: Truncate	$U_1 = 0.92$	$U_2 = 1$	227.5	135	$0.92C_1 + 0.01634C_2$	$C_1 + 0.015C_2$	$\mathcal{M}_s^1 = \{m_4, m_5, m_6, m_7\}$ $\mathcal{M}_s^2 = \{m_2, m_3\}$	The system is not time-feasible to send m_7 neither on $Channel_1$ nor on $Channel_2$, and $Channel_2$ is fully charged, i.e., $U_2 = 1$, so both Balance and Dilute strategies cannot work. Grape strategy gives new period $T_1 = 829.3$ for message m_1 but this period exceeds its maximum deadline $Dmax_1$. Thus, the system runs Truncate strategy to delete m_1 which has the lowest priority and add m_7.
At t_7 run: Balance/Dilute	$U_1 = 0.9956$	$U_2 = 0.97$	254.4	136.5	$0.9956C_1 + 0.02134C_2$	$0.97C_1 + 0.015C_2$	$\mathcal{M}_s^1 = \{m_4, m_5, m_6, m_7, m_8\}$ $\mathcal{M}_s^2 = \{m_2, m_8\}$	The system is not time-feasible to send m_8 neither on the both channels $Channel_1$ and $Channel_2$ nor by using Grape strategy, then after using truncate strategy to delete m_3 which has the lowest priority, the system can use Balance and Dilute strategies. Balance strategy adds this message m_8 on both channels by dividing its $WCTT_8$ into $WCTT_{8,1} = 16$ and $WCTT_{8,2} = 34$. Dilute strategy can add message m_8 by lengthening its period over three channels (i.e., $\mathcal{C}_n = 3$), but $\mathcal{C}_n > \mathcal{C}$, so the node cannot use Dilute strategy.
At t_8 run: Grape	$U_1 = 0.9956$	$U_2 = 0.99$	254.4	184	$0.9956C_1 + 0.02134C_2$	$0.99C_1 + 0.01537C_2$	$\mathcal{M}_s^1 = \{m_4, m_5, m_6, m_7, m_8\}$ $\mathcal{M}_s^2 = \{m_2, m_8, m_9\}$	The system is not time-feasible to send m_9 neither on both channels $Channel_1$ and $Channel_2$ nor by using one of both Balance and Dilute strategies. Using Grape strategy that changes the period of message m_2 to $T_2 = 186.05$, the system will be finally time-feasible to send m_9 on $Channel_2$.

for priority messages are the highest ones compared with the considered strategies (EHD, DMP, RTQS, DPSC_PR/DPSC_FR, and GlobalScheduler). Specifically, the percentage of adding the highest priority messages (messages with priority between 7 and 10) with deadline success is around 85%, and can go up to 100%. since the previous related works are limited to a situation in which the system becomes nonfeasible in time or energy to add more messages, whereas the proposed strategies make the nonfeasible system feasible in time and energy to add more messages by: dividing message WCTTs on multiple channels, adjusting message periods and sending each message over multiple channels, lengthening the periods of the lowest priority messages, or deleting them to add the highest ones; these differ from the existing works.

2) The message addition success rates achieved by EHD, DMP, DPSC_PR/DPSC_FR, and GlobalScheduler do not exceed 20% for all message priorities, since these research works are adding messages without considering their priorities, and in the case when the system becomes nonfeasible in time or energy, they do not provide any reconfigurable solution to add more messages.
3) The message addition success rates achieved by RTQS do not exceed 40% for all message priorities, although this paper deals with message priorities. The message priorities test is not done at run time, and there is no reconfigurable solution when the

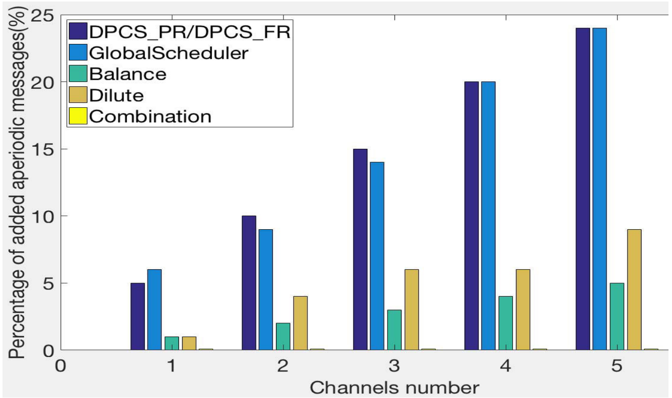

Fig. 4. Percentage of aperiodic messages transmitted over multichannel.

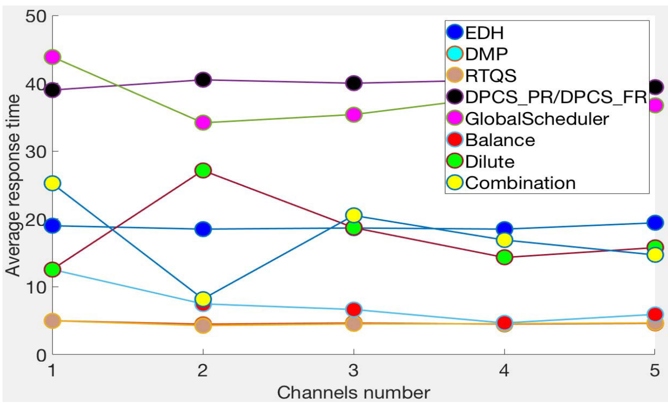

Fig. 5. Average response time of different scheduling strategies.

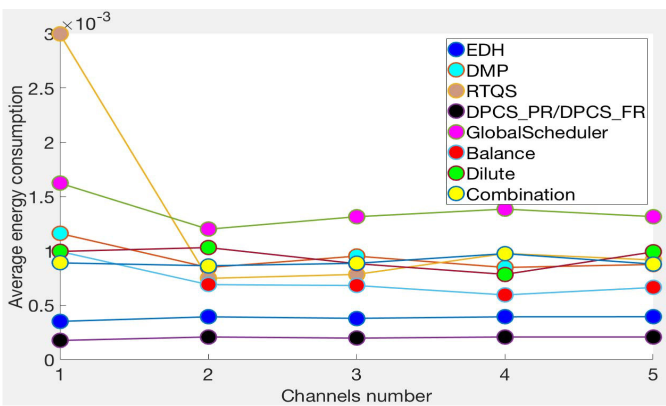

Fig. 6. Average energy consumption of different scheduling strategies at transmission mode.

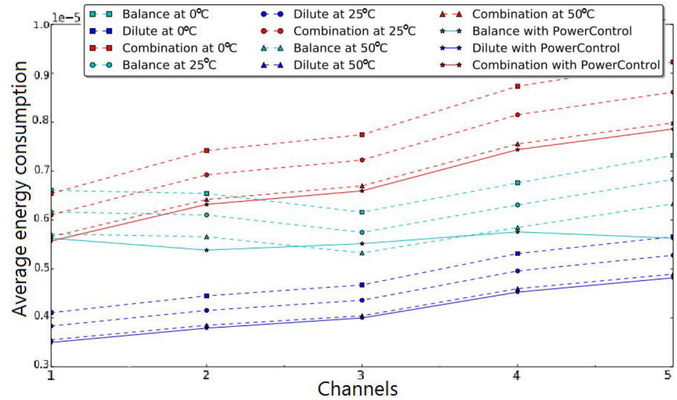

Fig. 7. Average energy consumption at transmission mode with using PowerControl strategy and without using it under three values of temperature $\tau = 0$ °C, $\tau = 25$ °C, and $\tau = 50$ °C.

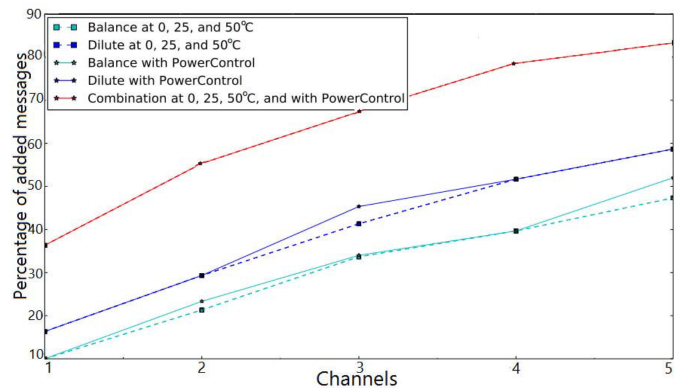

Fig. 8. Percentage of adding messages with using PowerControl strategy and without using it under three values of temperature $\tau = 0$ °C, $\tau = 25$ °C, and $\tau = 50$ °C.

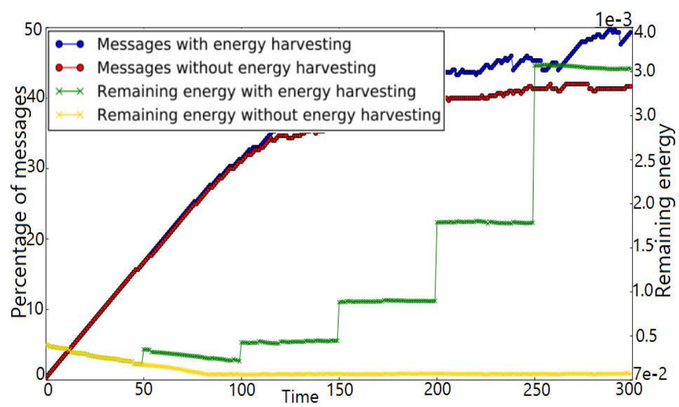

Fig. 9. Percentage of messages transmitted over multichannel by Balance strategy with the use of energy harvesting each 50 time unites.

system becomes nonfeasible to add the highest priority messages.

To evaluate the effect of managing the list of active channels on the performance of adding periodic messages in the considered strategies, a set of random periodic messages is coming with the same WCTT and random period and priority (priorities between 1 and 10), while messages are added sequentially according to their arrival time. Then, we run a series of simulation by varying the number of channels and plot the message addition success rate in Fig. 3, where:

1) in the case of one channel:
   a) the message addition success rate achieved by strategies Balance and Dilute does not exceed 10%, whereas it goes up to 20% after using the combination of them (i.e., Balance and Dilute together);
   b) the message addition success rate achieved by EDH, DMP, and DPSC_PR/DPSC_FR does not exceed 8%, whereas the addition success rate achieved by the strategies RTQS and GlobalScheduler is the lowest one compared with the other considered strategies.

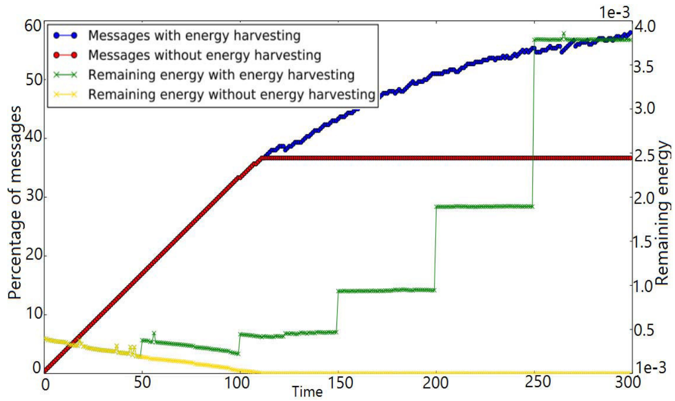

Fig. 10. Percentage of messages transmitted over multichannel by Dilute strategy with the use of energy harvesting each 50 time unites.

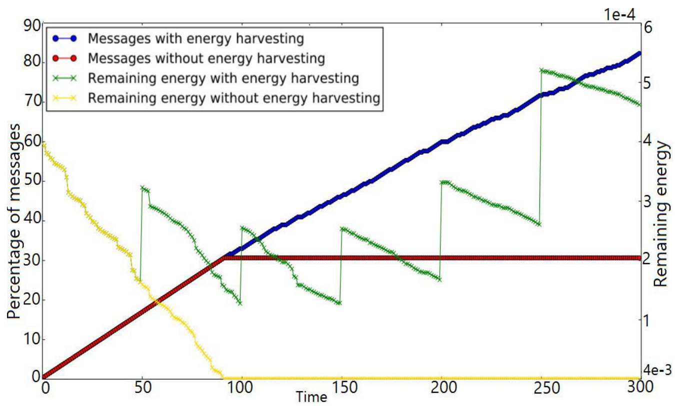

Fig. 11. Percentage of messages transmitted over multichannel by Combination strategy with the use of energy harvesting each 50 time unites.

We note that the proposed strategies achieve the highest addition success rate even on one channel, since they are maintaining system feasibility in time and energy to add more messages on one channel by: changing the periods of the lowest priority messages or deleting them to add the highest ones.

2) in the case of multiple channels:
   a) the proposed strategies continue to exhibit similar behavior by achieving higher addition success rates than the other considered strategies (EHD, DMP, RTQS, DPSC_PR/DPSC_FR, and GlobalScheduler), and Combination always achieves the highest one. With five channels, the message addition success rate achieved by Balance is around 70%, by Dilute around 40%, and by Combination around 85%;
   b) the message addition success rates achieved by the related strategies EDH, DMP, RTQS, DPSC_PR/DPSC_FR, and GlobalScheduler do not exceed 30%.

We note that adding more channels results in increasing the addition success rates, and the proposed strategies always achieve higher message addition success rates than the considered strategies EDH, DMP, RTQS, DPSC_PR/DPSC_FR, and GlobalScheduler, since the previous related works do not provide a solution to add messages when the system becomes nonfeasible in time or energy to add more messages, whereas the proposed strategies make the nonfeasible system feasible in time and energy to add more messages by: dividing message WCTTs on multiple channels, adjusting message periods and sending them over multiple channels, changing the periods of the lowest priority messages, or deleting them to add the highest ones.

To evaluate the effect of managing the list of active channels in this case study on the performance of aperiodic messages addition, a set of aperiodic messages is coming with the same WCTT, while messages are added sequentially according to their arrival time. As mentioned in Section IV-A, for the simulation, we choose to use a sporadic server for each channel with the proposed strategies for sending aperiodic messages (it is one of the periodic servers that are defined for adding aperiodic messages in the available slack time, see [44]). Thereafter, we run a series of simulation of the strategies that are interested in adding these messages, such as DPSC_PR/DPSC_FR and GlobalScheduler, then we plot the message addition success rate in Fig. 4, where:

1) the messages addition success rate achieved by the proposed strategies Balance and Dilute is increased symmetrically, where it is 1% for both strategies with one channel, and 5% for Balance and 8% for Dilute with five channels;
2) the messages addition success rate achieved by the strategy DPSC_PR/DPSC_FR is increased symmetrically, where it goes up to 5% with one channel and around 24% with five channels;
3) the messages addition success rate achieved by the strategy GlobalScheduler is increased symmetrically, where it is around 6% with one channel, and around 24% with five channels.

We note that the proposed strategies achieve the lowest message addition success rates, which means that the available slack time for the proposed strategies is shorter than the related works DPSC_PR/DPSC_FR and GlobalScheduler. We also note that Combination strategy does not participate in the addition of aperiodic messages for whatever channels number increased or decreased, which means that the available slack time (if it exists) is too short and not sufficient to send any aperiodic message. Since the proposed strategies (i.e., Balance, Dilute, and Combination) provide the highest success rate of adding periodic messages for whatever channels number increased or decreased, where the available slack time is used as much as possible to add more periodic messages by: dividing message WCTTs on multiple channels, adjusting message periods over multiple channels, and changing the period of the lowest priority messages to add the highest ones.

To evaluate the effect of managing the list of active channels in this case study on the response time of the considered strategies, a set of periodic and aperiodic messages is coming with the same WCTT, while messages are added sequentially according to their arrival time. Then, we run extensive simulations varying the number of channels from 1 to 5. Thereafter, we measure the response time for each successfully added message (periodic and aperiodic) for each simulation instance, and calculate the average response time that we define as the ratio between the sum of the response time of each successful message over the number of all successful added messages, then, we plot the obtained results in Fig. 5, where:

1) in the case of one channel: the averages response time provided by EDH, Balance, Dilute, and Combination strategies are close to each other, whereas DPSC_PR/DPSC_FR and GlobalScheduler provide the highest ones, and DMP and RTQS provide the lowest one;
2) in the case of multiple channels:
   a) the average response time provided by the strategy EDH is a bit constant and lower than what is provided by DPSC_PR/DPSC_FR and GlobalScheduler for whatever channels number increased or decreased. Note that this strategy uses EDF for messages scheduling;
   b) the average response time provided by the strategies DMP and RTQS are the lowest ones for whatever channels number increased or decreased, since these strategies provided a short response time with a low messages addition success rate. Note that this strategy uses FCFS for messages scheduling;
   c) the average response time provided by the strategy DPSC_PR/DPSC_FR is the highest one over multiple channels. Note that this strategy uses EDF for periodic messages scheduling while sending aperiodic ones in the available slack time;
   d) the average response time provided by the strategy GlobalScheduler is decreased after using multiple channels, but still higher than the other considered strategies except DPSC_PR/DPSC_FR. Note that this strategy uses RM for periodic messages scheduling while sending aperiodic ones in the available slack time;
   e) the average response time provided by the Combination strategy has decreased significantly after using two channels; then, it increased a bit as channels number increases, but still lower than what is provided by EDH, DPSC_PR/DPSC_FR, and GlobalScheduler, since these strategies are providing a long response time with alow message addition success rate, whereas Combination provides the highest message addition success rate with a short response time. Note that this strategy uses EDF to schedule the periodic messages;
   f) the average response time Balance is slightly decreased as channels number increases, and becomes the lowest one as DMP and RTQS, whereas the average provided by Dilute has decreased significantly after using two channels, then decreases as channels number increases. However, the average response time provided by these strategies is lower than the related works EDH, DPSC_PR/DPSC_FR, GlobalScheduler, and Combination. Since these strategies are providing a short response time with high message addition success rates. Note that these strategies use EDF to schedule the periodic messages and sporadic servers to send the aperiodic ones.

We note that Combination provides an average response time higher than the considered strategies: DMP, RTQS, Balance, and Dilute, since it provides the highest message addition success rate, which requires more time, so it provides a long response time. However, the provided response time is lower than the other related works: EDH, DPSC_PR/DPSC_FR, and GlobalScheduler.

To evaluate the effect of managing the list of active channels in this case study on the energy efficiency of the considered strategies, a set of periodic and aperiodic messages is coming with the same WCTT, while messages are added sequentially according to their arrival time. Then, we run extensive simulations and measure the average energy consumption of each strategy. Thereafter, we define the average energy consumption as the ratio of the sum of energy consumption of each successful message over the number of all successful added messages (periodic and aperiodic), then we plot the obtained results in Fig. 6, where:

1) in case of one channel:
   a) the average energy consumption provided by DMP, Balance, Dilute, and Combination strategies are close to each other, whereas RTQS and GlobalScheduler provide the highest ones, and EDH and DPSC_PR/DPSC_FR provide the lowest one.
2) in the case of multiple channels:
   a) the average energy consumption response time provided by the strategy EDH is a bit constant and lower than what is provided by the considered strategies except DPSC_PR/DPSC_FR for whatever channels number increased or decreased;
   b) the average energy consumption provided by the strategies DMP is slightly decreased as channels number increases, but is still higher than EDH, DPSC_PR/DPSC_FR, Balance, and Dilute;
   c) the average energy consumption provided by the strategies RTQS has decreased significantly after using multiple channels, and becomes close to the other considered strategies DMP and Combination;
   d) the average energy consumption provided by the strategy DPSC_PR/DPSC_FR is the lowest one for whatever channels number increased or decreased;
   e) the average energy consumption provided by the strategy GlobalScheduler is slightly decreased as channels number increases, but is still the highest one over multiple channels;
   f) the average energy consumption provided by the Combination strategy is slightly increased; then it decreases as number of channels increases, but is still higher than the related works: EDH, DPSC_PR/DPSC_FR, and Balance, since this strategy provides the highest message addition

success rate, which requires more energy consumption;

g) the average energy consumption Balance and Dilute is slightly decreased as channels number increases, but is still higher than the related work: EDH and DPSC_PR/DPSC_FR, since Balance and Dilute are providing higher message addition success rates than the other considered strategies except Combination, which requires more energy consumption.

In addition to varying the number of channels and to minimize the energy consumption in transmission, we use the smallest input current in transmission that is sufficient enough for the transmitted message to reach the destination (PowerControl). We evaluate the performance of PowerControl depending on the temperature variation with the considered strategies. Since the communication range varies according to temperature variations, which has an effect on the transmission power and reception sensitivity, where when the temperature decreases (resp. increase), both transmission power and reception sensitivity increase (resp. decrease), we run a series of simulations varying the environment temperature from 0 °C to 50 °C. We specifically measure the values for three temperature values: 0 °C, 25 °C, and 50 °C. We plot the obtained results in Fig. 7 which shows that PowerControl further reduces the consumed energy in transmission mode. In fact, when temperature changes, the PowerControl algorithm varies the input current necessary for a successful transmission and thus guarantees that optimal input current is used according to the observed environment temperature. Fig. 8 shows the message addition success rate when a node run with/without using PowerControl, which proves that PowerControl helps the proposed strategies to achieve a higher message addition success rate.

We show in Figs. 9–11 the effect of energy harvesting on adding messages for each strategy alone, i.e., Balance, Dilute, and Combination (respectively), where we divide the system time into time intervals with a length equal to 50 time units. At the beginning of each time interval, we harvest the energy and estimate its value, then we compare the message addition success rate given by the proposed strategies with and without the use of energy harvesting, where we note that the use of energy harvesting helps the proposed strategies to obtain a higher message addition success rate. In this case study, we note that the message addition success rate can be increased from 40% to 50% after using the Balance strategy, from 35% to 58% after using the Dilute strategy, and from 30% to 90% after using the Combination strategy as much as energy can be harvested. Otherwise, when the energy harvesting is not available, the message addition success rate will be constant over time.

The conducted experiments show that when the RWSN applies the proposed strategies on a multichannel configuration, significant improvements can be obtained compared to state-of-the-art methods, particularly in situations where energy can be harvested by the sensor nodes. We show that we achieve a high percentage of adding messages under time and energy constraints with lower response time and energy consumption.

VII. Conclusion

In this paper, we focus on message scheduling in multichannel real-time RWSN under energy and time constraints. We focus on developing scheduling strategies to guarantee that all messages are scheduled successfully with the lowest energy consumption and response time. The proposed scheduling strategies make sure that the system is time-feasible and energy-feasible to send all messages while guaranteeing that the highest priority messages are scheduled. We have proposed original strategies, i.e., Balance, Dilute, and Combination, with the goal of achieving both time and energy feasibility. Within these strategies, we rely on: 1) Enable/disable channels; 2) Grape; and 3) Truncate technical solutions which we have designed to handle all possible cases that cannot be directly handled by the global strategies. For energy efficiency, we propose to use PowerControl which achieves the lowest energy consumption in transmission by using the optimal input current.

Extensive simulation experiments show that the Balance, Dilute, and Combination strategies achieve a significant improvement over the existing methods. We show that these strategies achieve a percentage of success of about 85% in adding the highest priority messages while meeting deadlines, and in some situations, it can go up to reach 100% of priority message scheduling success rates. We also show that these strategies realize the highest percentage of adding all types of messages either on one or multiple channels while ensuring the deadline success of all scheduled messages with a lower average energy consumption and lower average response time than other existing methods.

As a future work, we plan to manage the concurrent reconfiguration events to observe the transmission of real-time messages and lifetime of nodes. We also plan to extend the proposed approach to heterogeneous real-time RWSN with an advanced network topology and develop a distributed scheduling in those reconfigurations.

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