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Evaluating Reliability of WSN with Sleep/Wake-up Interfering Nodes

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Abstract

A Wireless Sensor Network (WSN)[1] is a distributed system composed of autonomous sensor nodes wireless connected and randomly scattered into a geographical area to cooperatively monitor physical or environmental conditions. Adequate techniques and strategies are required to manage a WSN in order it properly works, observing specific quantities and metrics to evaluate the WSN operational conditions. Among them, one of the most important is the reliability.

Considering a WSN as a system composed of sensor nodes the system reliability approach can be applied thus expressing the WSN reliability in terms of its nodes' reliability. More specifically, since often standby power management policies are applied at node level and interferences among nodes may arise, a WSN can be considered as a dynamic system. In this paper we therefore consider the WSN reliability evaluation problem from the dynamic system reliability perspective. Static-structural interactions are specified by the WSN topology. Sleep/wake-up standby policies and interferences due to wireless communications can be instead considered as dynamic aspects. Thus, in order to represent and to evaluate the WSN reliability we use dynamic reliability block diagrams and Petri nets. The proposed technique allows to overcome the limits of Markov models when considering non-linear discharge processes, since they cannot adequately represent the aging processes. In order to demonstrate the effectiveness of the technique we investigate some specific WSN network topologies, providing guidelines for their representation and evaluation.

I. INTRODUCTION

Wireless Sensor Networks are networks of tiny sensors equipped with radio interfaces for communicating. They are used to cover large-geographical areas on which they are usually randomly distributed, by periodically performing measurements that are therefore sent to the sink node for processing and storing. Their application fields range from disaster recovery to agriculture monitoring, from industrial processes to traffic-pollution monitoring, and so on. Several of such specific applications have also strict dependability requirements [1], [2] that have to be satisfied through sensors usually powered by low voltage batteries limiting their lifetime. We can argue that a WSN is a power-constrained system.

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[1] Singular and plural of acronyms are spelled the same.

In order to optimize the power management with the aim of maximizing the WSN reliability by reducing and minimizing the node energy consumption, a common practice is to switch WSN nodes into a lower powered state, identified as sleep mode, by deactivating the radio when no data has to be transmitted [3]. By associating the battery discharge to the WSN node aging process as in [3], [4], [5], [6], [7], the node reliability can be identified and associated to the battery charge level. Another aspect that can affect the WSN reliability is the interference among nodes that has a negative impact on the node reliability due to the energy waste for retransmissions.

In terms of reliability a WSN can be considered as a systems aggregating nodes/components, which reliability can be therefore expressed as function of such components reliability. More specifically a WSN is a dynamic system since standby policies and interferences affect its nodes/components, while the components' structural relationships are identified by the network topology. Different network topologies can be specified and consequently different data routing strategies have to be implemented (either single- or multi-hop).

According to such considerations, in order to adequately evaluate the WSN reliability, dynamic reliability techniques are required. In this work we propose to use dynamic reliability block diagrams (DRBD) [8], [9], [10] for modeling the WSN dynamic reliability. DRBD extend the classic combinatorial RBD to the modeling of dynamic reliability aspects and behaviours. They allow to represent a wide range of dynamic reliability aspects through a compositional-modular approach based on the concept of simple dependency, specifying different ways and mechanisms for composing such dependencies. However, it is important to remark that DRBD are only a modeling technique and therefore, once obtained the DRBD model it is necessary to translate it into a specific solution model (Markov chain, Petri net, simulation, etc.).

Aim of this work is therefore to evaluate the reliability of a WSN considering a system reliability perspective through the DRBD modeling approach. We firstly focus on dynamic aspects at node level (standby management, interferences), then we take into account static/structural relationships related to different network topologies. The technique is applied to some specific examples related to the different topologies evaluated, thus providing an in depth comparative investigation of their reliability. In order to evaluate the DRBD we translate them into the corresponding Petri nets as specified in [10], [9], applying the technique proposed in [7]. In particular, in order to adequately model any possible time-to-failure distributions as well as the sleep/wake-up timers, non-Markovian stochastic Petri nets have been used, since they allow to represent both Markovian and non-Markovian distributions.

In the last years, researches on WSN have mainly focused on networking aspects [11], [12] as well as on data management [13]. More recently, several work deals with WSN reliability and power management topics. An interesting investigation is performed in [5], in which the authors propose a simulation technique for evaluating blind flooding over WSN. Although the goal of such work is different from our, the battery model used is really interesting and represents a significant reference. The problem of WSN reliability and power management has also been investigated through the use of analytical models. For example, in [4] Markov models are used in order to evaluate WSN reliability, while in [6] a Markov reward model is adopted.

One of the main contribution of the approach proposed in this paper is to consider non-linear discharge process, corresponding to general time-to-failure distributions, in dynamic contexts, problem that cannot be adequately addressed through Markov models. With specific regards to [7], in this work we also consider interferences among nodes, approaching the problem in a different way, from the system reliability perspective, thus also considering the network topologies, that can be considered as a further original contribution of this paper. To the best of our knowledge this is the first attempt to investigate the WSN reliability considering both interferences and standby management policies at node level by applying a system reliability technique. Moreover, it is necessary to remark that no assumption or restriction on the node/component reliability is specified, therefore any time-to-failure cumulative distribution function (CDF) can be considered.

The remainder of the paper is organized as follows: in Section III an overview of WSN reliability while Section IV introduces DRBD. Section V deals with WSN dynamic and structural aspects modeling, respectively. The proposed models are then evaluated in Section VI, then Section II critically discusses the related work while Section VII closes the paper with some final remarks.

II. RELATED WORK

In the last years, researches on WSN have mainly focused on networking aspects [11], [12] as well as on data management [13]. However, many specific applications introduce strict dependability requirements [1], [2] that are primarily related to data security and reliability [14] and to the reliability of the single node and the WSN as a whole [15], [3], [4], [5], [16], [17].

In such specific context an important, primary characteristic to ensure is *resilience* [18], [19]. Resilience is the ability of the network to provide and maintain an acceptable level of service in the face of various faults and challenges to normal operation [20]. There is a close relation between dependability and resilience, as also highlighted and studied in depth in [21] where resilience has been defined as the persistence of dependability when facing “changes”. Such a wider concept can be decomposed into sub-concepts/characteristics such as survivability [15], fault tolerance [22], etc. With specific regards to WSN, this is primarily associated to the reliability since nodes run on limited power batteries.

In order to reduce and optimize the energy consumption, a common practice is to switch WSN nodes into a lower powered state, usually identified as *sleep mode*, by deactivating the radio equipments when no data have to be transmitted [3]. Since quite often the radio is the highest power consumer subsystem in a WSN node, this allows to save battery and therefore to improve the node lifetime. In this way, by associating the battery discharge to the WSN node aging process as in [3], [4], [5], the node longevity can be expressed, in terms of reliability, as a function of the *battery state of charge*.

Several authors deal with WSN and power management topics, at different layers and achieving different goals. In the specific context of reliability, an interesting investigation is performed in [5], where a simulation technique for evaluating blind flooding over WSN is proposed. The authors base the evaluation on a realistic and accurate battery model, also considering *capacity* and *recovery effects* as well as *switching energy*, instead of starting from the linear discharge model usually assumed in literature.

The choice of the battery model is of primary importance in evaluating the WSN longevity as also highlighted in

[16]. Mathematical battery models are usually used in the node/WSN longevity and power management modeling and evaluation. For example, in [17] a new sensor node deployment scheme is proposed to increase the sensor network reliability assuming a non-linear battery discharge model. More recently, [16] proposes a flexible and extensible simulation framework to estimate power consumption of sensor network applications for arbitrary hardware platforms in which energy and timing parameters are partially obtained through direct measurements.

The problem of WSN reliability and power management has also been investigated through the use of analytical models. For example, in [4] Markov models are used in order to evaluate WSN reliability. In such case the context is slightly different: WSN composed of several nodes are considered and the final model reflects such choice, representing the WSN as a whole and introducing some higher level approximations.

An interesting technique for evaluating the reliability of WSN with arbitrary topologies is proposed in [23], by using two alternative algorithms based on the graph theory, providing two special cases where they are efficient (polynomial time). The work has been then further extended in [24] providing some approximated technique for evaluating the WSN reliability.

One of the first work that highlight the necessity of considering dynamic aspects and behaviors in WSN reliability evaluation was [25]. Following that way, in [26] the reliability of clustered WSN subject to common cause failures is evaluated using an efficient progressive reduction algorithm based on reduced ordered binary decision diagrams. Such work has been then extended by comparing different topologies in [27], and by considering different fault tolerance and intrusion detection strategies and configurations in [22], [14] using dynamic fault trees.

Some works use Petri nets for modeling and analysing WSN. For example, in [28] a generalized stochastic PN is exploited for representing the WSN power consumption. Only exponential events can be therefore represented by such technique. A technique for evaluating the WSN dependability through stochastic activity networks (SAN) is proposed in [29]. The failure modes of sensor nodes have been modeled as a set of SAN, following the results of a detailed FMEA. In this way the authors can deal with run-time network reconfigurations using real WSN parameters from FMEA and thus providing quantitative evaluation of dependability attributes. But no dynamic-dependent behaviors such as sleep/wake-up or interference are considered. In [6] NMSPN are used to evaluate the reliability of a sleep/wake-up node. A memory based on time is implemented to just represent linear battery discharge process through a pre-emptive resume policy (prs) on the failure transition CDF. Although it is based on NMSPN such technique is therefore limited in the failure distribution modeling.

With regards all the above referred techniques, the one proposed in this paper allows to adequately represent the reliability of a WSN whose node lifetimes are generally distributed, properly applying the conservation of reliability principle and without any restriction on the CDF allowed. Both sleep/wake-up policies and interferences among nodes are taken into account, evaluating the three main WSN topologies. The DRBD-NMSPN technique thus proposed has no restriction in WSN modeling and evaluation, but it could suffer of the state space explosion problem affecting state space-based models. Therefore, the WSN complexity could be a problem for such a technique. A possible solution is to recur to symbolic techniques to represent the state space or to exploit symmetry and lumping of the PN. Another way is to implement a hierarchical technique based on that proposed in this work, on top of which combinatorial models can be built to aggregate the sub-models thus specified.

III. PROBLEM FORMULATION

Aim of this section is to clearly state the concepts and the quantities characterizing the WSN reliability evaluation problem.

Usually, in real applications, wireless sensor nodes are randomly scattered in large geographical regions not covered by power suppliers and moreover hard to reach for performing node maintenance after deployment. Sensor nodes must therefore be autonomous in power, adapting their power-consumption profile to environmental changes. Usually the power autonomy is achieved by equipping WSN nodes with batteries characterized by finite, limited charge that correspond to limited operating time of the node.

A technique to extend the nodes operating time could be to use sources of alternative energy (sun, heat, wind, etc.) to recharge them. But to provide nodes with such recharging system is really expensive. A more efficient power management strategy is to reduce and to minimize the node power consumption thus optimizing the battery discharge process.

Several other phenomena can affect a node reliability, such as physical defects and faults on the node devices (radio, sensors, micro-controller) or software (operating system) faults. Also external causes may arise (meteorological phenomena, rain, flooding, natural disaster, catastrophes, geomagnetic storms, etc.) involving different nodes in a common cause failure effect. The node status in WSN can be classified into two types [30] *normal* and *faulty*. Node faults can be grouped into two categories: *hard* if the node cannot communicate with other nodes due to the failure of a certain device, and *soft* if the failed nodes can continue to work and communicate with other nodes but the data sensed or transmitted is not correct.

However, considering only hard faults that are detectable, the main failure cause for a sensor node is the battery depletion. There are several orders of magnitude between the node battery depletion (which mean time is usually expressed in hours) and physical faults (which mean time is usually expressed in years) as well as external causes (mean time of years). Therefore a common practice is to consider the battery depletion as the only cause of failure for a WSN node [4], [5], [6], [7], thus neglecting the other causes. In the following we therefore assume that the battery depletion is the only cause of failure for a sensor node. Thus, we define the reliability of a sensor node at time t, $R(t)$ as:

Definition 3.1: The reliability of a sensor node at time t, $R(t)$, is the probability that its battery is not depleted in the time interval $[0, t]$.

$$R(t) = Pr\{c(t) \geq c_{min}\}. \tag{1}$$

where $c(t)$ is the discharge function of the node battery, expressing and quantifying its charge at time instant t.

Generally sensor nodes are composed of a processing unit, a wireless communication unit (the radio), and a sensing unit. Communications can be considered the highest power-consuming operations in WSN nodes [4]. An effective strategy in order to reduce power consumption is to activate the radio only when the node has to communicate, kept it deactivated otherwise. In this way, nodes periodically switch between two different functioning states: active and sleep. When the node is in the active state, it is able to send/receive data while, when sleeping, it is only able to perform off-line tasks such as sensing and data processing.

In order to analyze the battery discharge process and the reliability as specified in eq. (1) of a node sensor with sleep/wake-up cycles, it is necessary to associate to each operating mode a battery discharge function, namely $c_A(t)$ and $c_S(t)$, respectively in the active and in the sleep state. In this way, the node discharge function $c(t)$ can be expressed as a function of both $c_A(t)$ and $c_S(t)$, such as a linear-weighted combination or a more complex equation of these latter, depending on the discharge model considered and on the accuracy level required. It is important to remark that, in case of higher precision models, it is necessary to preserve the battery charge level reached in the switching from an operating condition to the other [7].

Such information significantly influences the choice of the technique used in the evaluation of the node reliability since, in case of non-linear battery discharge processes, the charge to preserve could not be directly related to time, so the associated stochastic process has to conserve a quantity that is function of time and not directly the time. This means that Markov, semi-Markov and renewal theory models, for example, are not able to represent such behaviors, fluid models or (phase type) approximated models have to be used instead [7].

IV. DRBD

Dynamic reliability block diagrams (DRBD) are an extension of common reliability block diagrams (RBD) to dynamic aspects and behaviors modeling.

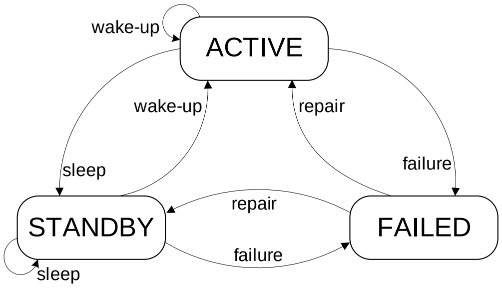
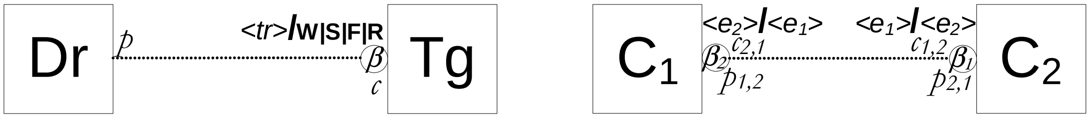


Fig. 1: DRBD unit finite state machine

Two are the key points of a DRBD: the *unit dynamics* characterization and the concept of *simple dependency*. More specifically, in a DRBD model each unit is characterized through a variable *state* identifying its operational condition at a given time. The evolution of the state of a unit, the unit dynamics, consists of the *events* occurring to it. The states of a generic DRBD unit are of three types, as shown in Fig. 1: *active* if the unit works without any problem, *failed* if the unit is not operational, following up its failure, and *standby* if it is reliable but not available. A unit state is completely defined by its time-to-failure (for active or standby states) or time-to-repair (in case of failed states) CDF.

An event represents the transition from a unit state to another one: the *failure* event models a change from active or standby to failed states, *wake-up* switches from active or standby to active states, *sleep* from standby or active to standby states, and the *repair* from failed to standby or active states. The transitions within the same state are related to the dependencies' *concurrency* management [31]. The initial state of a unit is the fully active state, except in cases there are incoming dependencies to be initially satisfied.



(a) Simple (b) Mutual

Fig. 2: DRBD one-way/simple and two-way/mutual dependencies

A dependency can be considered as a *cause/effect* relationship. Referring to Fig. 2a showing a generic DRBD dependency representation, the *cause* of a dependency is referable to the occurrence of a specific event (*trigger* $< tr >$) on the *driver* unit (Dr). As a consequence, the *effect* of a dependency is instead referable to a specific (*reaction* $W|S|F|R$) event forced by the former on the *target* unit (Tg). Between trigger and reaction occurrences, the dependency *propagation* models the application of a dependency and it is expressed by the *propagation probability* (p).

The effects of a propagated dependency are instead quantifiable in terms of reliability and/or maintenance CDFs. When a dependency is applied and propagated to the target dependent unit Tg, the corresponding time-to-failure (time-to-repair in case of failed unit) CDF changes. Such change is quantified in the state reached by the dependency application (*reaction state*) through the corresponding CDF. Four types of trigger and reaction events can be identified: wake-up (W), repair (R), sleep (S) and failure (F). Combining actions and reactions, 16 types of simple dependencies are identified.

In the examples shown in Fig. 2a, trigger and reaction events are identified by a string close to the circle identifying the target side. In case of composition among dependencies the composed trigger event is represented as a condition of the simple triggers, as introduced above.

Mutual dependencies represent reciprocal influences between two units. Each unit is, at the same time, target and driver of a dependency on the other unit. More specifically, the trigger of each dependency pair must be of the same type/class (sleep, failure, wake-up, repair), as depicted in Figure 2b. The two dependencies quantify the mutual effects on each unit separately, also considering their feedback.

The composition of dependencies is an operation involving two or more units, each specifying a simple dependency incoming to the same target. The result of such operation is still a (*"composed"*) dependency. The composition mechanism can be evaluated in terms of both cause and effect of a dependency. In terms of causes the dependencies' composition is implemented by aggregating the drivers of the simple dependencies and the corresponding triggers into a *"composed"* trigger event (*event composition*). Several basic relationships among events can be identified: *temporal* ($>, <, =, \geq, \leq, \neq$) specifying the temporal order among events' occurrence, and/or *logical* (AND, OR, NOT, XOR, NAND, NOR, XNOR) specifying logical-Boolean conditions among events' occurrence. By combining the events using such operators a composed trigger event of a dependency can be specified.

In terms of effects, the composition among dependencies can be implemented in two ways: *concurrent/mutually exclusive* or *cooperating/overlapped*. In the former case, the effects of the dependencies to be composed are mutually exclusive: only a dependency at time can be applied to the target. DRBD solve this problem by discriminating the conflicting dependencies according to a *priorities evaluation algorithm* that establishes the unique *winner* dependency.

On the other hand, *cooperating/overlapped* dependencies identify a special case of dependencies composition. The assumption regulating *cooperating/overlapped* dependencies composition is that all the dependencies to be composed must have *compatible* or *equal* reactions. If such assumption is satisfied, the effects of the overlapping compatible dependencies are merged according to a specific *merging function* [31], [8]. This is a powerful and flexible mechanism, allowing to model several dynamic aspects such as load sharing effects, multi-source interferences, limited or insufficient repairmen resources, maintenance policies, fault coverage, etc.

Further details on DRBD can be found in [9], [10], [31], [8].

V. WSN MODELING

Aim of this section is the modeling of WSN following a dynamic system reliability approach. In order to clearly explain our approach, in subsection V-A we firstly focus on node level, explaining how to represent the dynamic behaviors that affect the WSN nodes, i.e. interferences and sleep/wake-up standby policies, through DRBD. Then, in subsection V-B, we move at network level, dealing with the WSN topology that mainly refers to static-structural reliability aspects. In doing so, we start from the node models, explaining how nodes interact according to the different topologies, catching their interactions into a whole WSN DRBD model. In light of the models thus specified, the DRBD modeling choice is motivated in particular against the DFT approach in subsection V-C.

A. Node Level - Dynamic Reliability

The goal of this subsection is to specify how to represent WSN node reliability through DRBD. In this way we implicitly consider a WSN node as a dynamic reliability system, composed of nodes and sinks that are wireless connected according to a specific topology, which identifies the static-structural reliability connections among blocks/nodes. But the nodes can also be considered, from a reliability perspective, as dynamic, since they can interfere each other. Moreover, they have two possible operating modes, active and sleep.

Let's start the DRBD modeling by considering the node point of view. As mentioned above two modes of operating are identified for a node, the active and the sleep ones. Generally speaking, more than one standby condition can be characterized for the same node, as for example in the ZigBee (IEEE 802.15.4) MAC layer where power-down and idle identify two different sleeps of the radio device characterized by the corresponding discharge currents. Other parameters to take into account are the whole sleep/wake-up period (beacon interval in ZigBee) and the active period (superframe duration), by which all the other parameters, such as the sleep period and the duty cycle (ratio between the active period and the whole sleep/wake-up period), can be obtained.

Such behavior can be represented in DRBD as a standby. But since in DRBD it is necessary to explicitly specify the element, the block that drives the active-sleep and sleep-active switching, it is necessary to introduce a specific element named *sleep controller* (sleep ctrl in Fig. 3). The sleep controller is a repairable component, which reliability function $R_{SC}(t)$ is associated to the sleep period and repair/maintenance function $M_{SC}(t)$ corresponds to the active period. These are usually deterministic distributions centered at the sleep and the active period, respectively. But sometimes, in cases there is uncertainty or randomness, for example due to unpredictable longer transmissions, $R_{SC}(t)$ and $M_{SC}(t)$ could be exponential distributions with sleep and active periods as mean values, respectively.

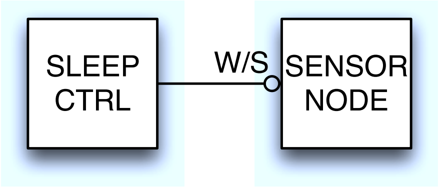


Fig. 3: DRBD of a generic sleep/wake-up sensor

In this way the DRBD of Fig. 3 is obtained. When the sleep ctrl is active (the sleep is triggered), the sensor node is in a low powered standby characterized by $R_{SN}(t)$ of eq. (1) corresponding to the lower standby current. Otherwise, when the sleep ctrl is failed, the node is in its active period characterized by $R_{AN}(t)$ associated to the current drained by the radio. In case of multiple sleep nodes it is necessary to model their management policy.

Referring to the ZigBee protocol that does not allow to mix different sleeps, it is necessary to initially set up the sleep that will be applied (power-down or idle). Anyway, different policies can be represented in DRBD by specifying a sleep controller for each identified sleep and therefore defining which of them has to be applied, adequately combining dependencies and setting priorities in case of conflicts.

Once the single node behavior has been represented, let's consider its interactions with the external environment. In a WSN, the nodes interact in order to exchange data through wireless links. This implies that, in the established connections, interferences from neighbour nodes can arise. This could impact on the reliability of each node and therefore on the WSN reliability since further battery charge is required in order to retransmit data.

Such interactions can be represented in DRBD terms through W/W mutual dependencies as shown in the example of Fig. 4: when a node is active it can interfere with other active nodes in its coverage area with consequent impact on its reliability. The coverage area shared by nodes 1, .., n is indicated in Fig. 4 by a dashed circle.

Since the probability of interferences increases with the number of interacting (active) nodes, the impact of interferences on reliability can be considered as a function of such parameter. We can therefore argue that the reliability of a sensor node depends on how many nodes are interacting with this, decreasing when the interferences increase. Such behavior is thus represented in DRBD as a cooperating overlapped dependency, whose merging function has to take into account all the interacting nodes reliability.

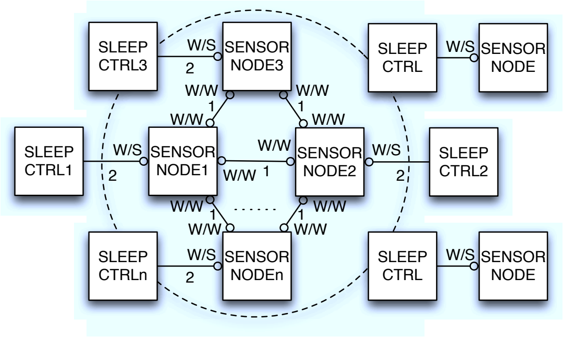


Fig. 4: DRBD example representing the interactions among different nodes.

Assuming that all the nodes are identical or identically distributed with failure rate in isolation, i.e., when it is not involved in any dependency, $\lambda_N(t)$, a possible merging function that can adequately represent such interactions on a specific node is:

$$\lambda_{ND}(t) = n^{\alpha}\lambda_N(t) \tag{2}$$

where $\lambda_{ND}(t)$ is the failure rate of the node interfering with $n-1$ nodes ($n > 0$) and $\alpha \in \mathbb{R}, \alpha \geq 0$ is instead the *interference parameter*, weighting the impact of interferences on the node reliability. Values of α close to 0 characterize low impacts of interferences on reliability, while values of $\alpha \geq 1$ represent strong impacts. $\lambda_{ND}(t)$ represents the failure rate of the node due to battery depletion. Eq. (2) can be considered as a generalization, the general formula of the failure rate when the battery discharge changes its trend due to interferences. In fact, if there are no interference with the other WSN nodes ($n = 1$), from eq. (2) we obtain that the node failure rate is that in isolation $\lambda_{ND}(t) = \lambda_N(t)$.

Another interesting aspect of the DRBD model of Fig. 4 concerns priorities. From the node point of view, the W/W dependencies conflict with the W/S dependency incoming from the sleep ctrl. Since this latter dependency represents the internal functioning of the node, it has greater priority ($c = 2$) than the W/W interference dependencies ($c = 1$). In this way the dependencies' conflict is unequivocally solved.

B. Network Level - Static Reliability

As introduced above, the WSN reliability depends on the network topology. In order to investigate network topology reliability issues we consider a generic WSN composed of n sensor nodes and one sink. The sensors send measured data (temperature, humidity, pressure, etc.) to the sink that collects and processes them. From the sink point of view, sensors are assumed to be equivalent, i.e., they perform the same function (sensing) in a specific area. In other terms, we assume the WSN contains a redundant number of sensors. Indeed, to properly extract the required information the sink has to receive data from at least k sensors, with $k \leq n$. The WSN reliability $R_{WSN}(t, k, n)$ can be therefore specified as [6]:

Definition 5.1: The reliability $R_{WSN}(t,k,n)$ of a WSN at time instant t is the probability that at least k of the n nodes are working properly in the time interval $[0,t]$.

$$R_{WSN}(t,k,n) = Pr\{k - out - of - n \text{ nodes are working properly in } [0,t]\}. \tag{3}$$

In this subsection, starting from the above results at node level, structural reliability relationships of star, cluster, and mesh WSN network topologies are investigated.

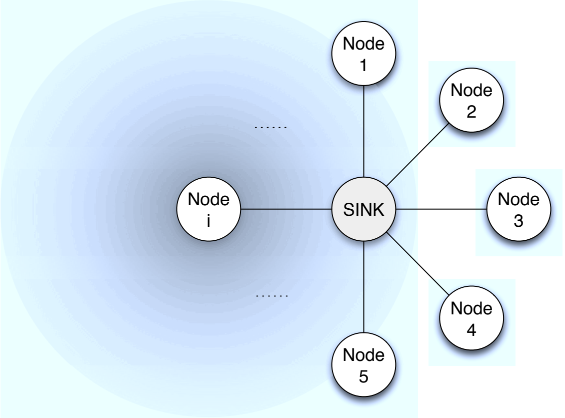


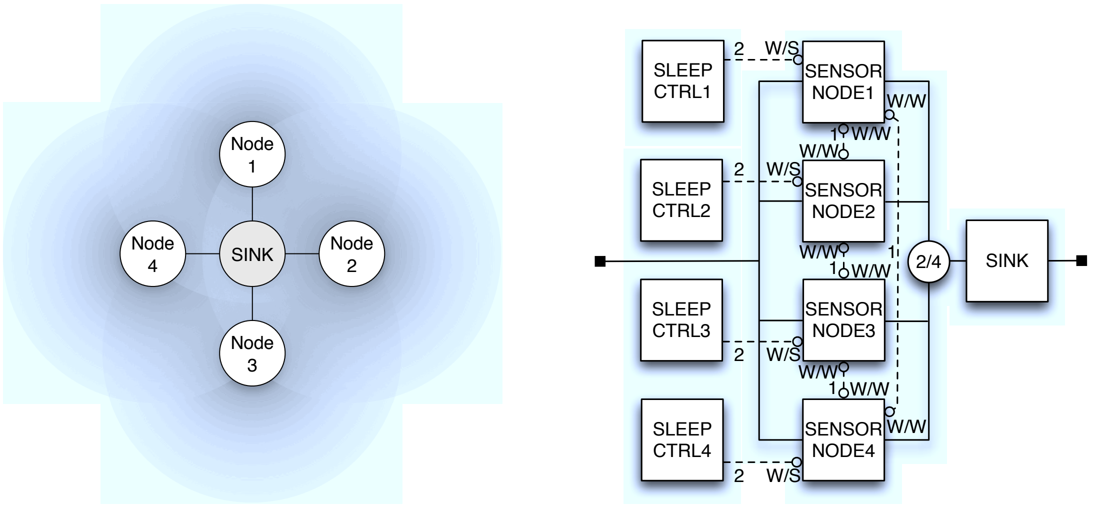
Fig. 5: A generic WSN star topology

1) Star topology: Now, let's consider a WSN composed of sensor nodes connected to one sink through a star topology as shown in Fig. 5. Each node has a direct connection to the sink and the node-sink communication does not involve other nodes (one/single hop routing). But, the nodes within the same coverage area can interfere. Thus, in the DRBD modeling of the star WSN topology it is necessary to take into account the interferences among the nodes.

In the example reported in Fig. 6, a 4-node star topology is represented. The interferences among nodes, in the specific example, mainly regard the two neighbours, as highlighted in Fig 6a. Thus, nodes 1 and 3 interferes with nodes 2 and 4 and vice versa. A 2-out-of-4 policy is considered for the WSN reliability of eq. (3), $R_{WSN*}(t,2,4)$, as reported in the corresponding DRBD of Fig. 6b (the 2/4 parallel structure). The DRBD also represents all the nodes interferences through W/W dependencies, while the sleep/wake-up switching is instead represented through the sleep ctrl and the corresponding W/S dependency.

2) Cluster topology: The main drawback of the star topology is the limitation on the network size, since the WSN coverage area is restricted to the maximum through the cluster topology. In cluster topology a hierarchy among nodes is established. In this way the route to the sink from each node is fixed and well known, but it is necessary the data is sent/forwarded to more than one node before it reaches the sink, in a multi-hop fashion. However each node always sent data, that could be own generated or data to forward, to the cluster head, that forwards this to its cluster head and so on, until the sink (the root of the cluster topology tree) is reached.

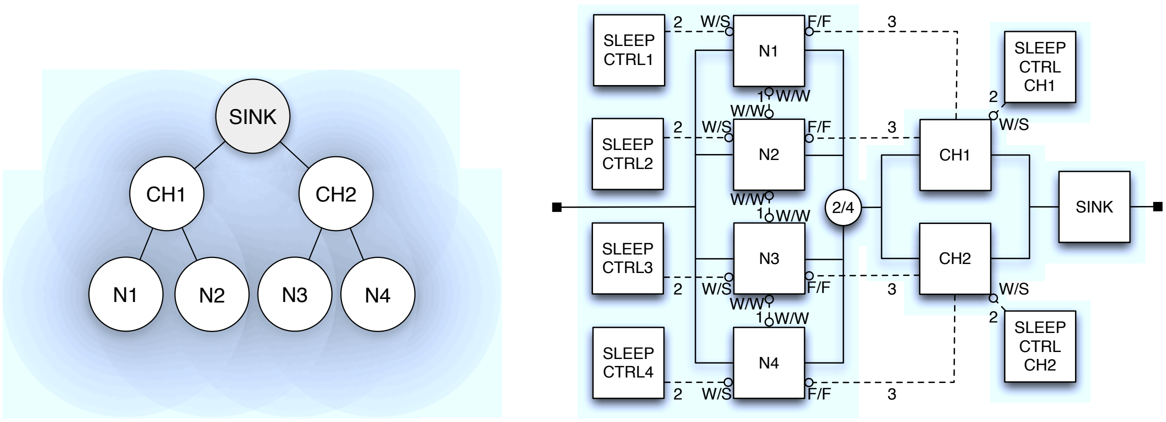
An example of a WSN cluster topology is shown in Fig. 7. Such topology is composed of 4 sensor nodes, N1-N4,



(a)

(b)

Fig. 6: A 4-node WSN star topology (a) and corresponding DRBD (b).



(a)

(b)

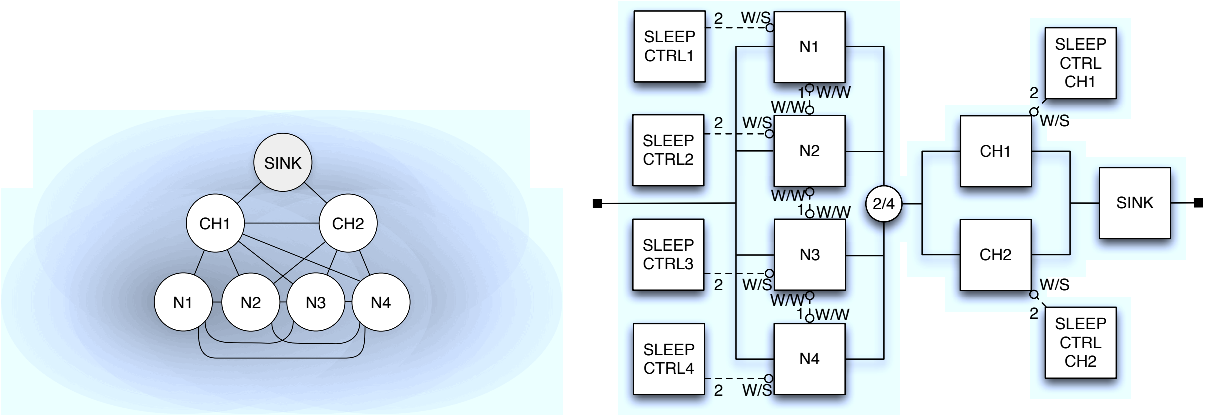
Fig. 7: A 4-node WSN cluster topology (a) and corresponding DRBD (b).

organized in two clusters with cluster heads CH1 and CH2 that only forward the received data, as shown in Fig. 7a.

A 2-out-of-4 configuration is considered as above, but in this case, if a cluster head fails, the associated nodes cannot be reached. This condition is represented in the corresponding DRBD of Fig. 7b by F/F dependencies: when a cluster head fails the corresponding nodes fail. Since such dependencies have to be ever applied when triggered, the highest connection priority (3) is associated to them.

3) Mesh topology: The main drawback of a cluster topology is that, when a cluster head node fails all its descendent in the cluster hierarchy tree are no more able to communicate with the sink. In order to increase the WSN reliability, a possible strategy is to create alternative paths by introducing redundant links on the network, thus obtaining a mesh topology. In this way, nodes can find alternative routes when a failure event occurs. To this end, the routing protocol has to be able to autonomously adapt to dynamic changes on the network topology.

Examples of 4-nodes mesh topologies, obtained by adding redundant connections to the cluster topology of Fig. 7a, are discussed in the following. As above, in such examples the cluster heads sensing is disabled and only used to forward data incoming from the level below. In particular three topologies are investigated according the connections among nodes and cluster heads: *all to all, fully* and *partially* connected mesh WSN.



(a)

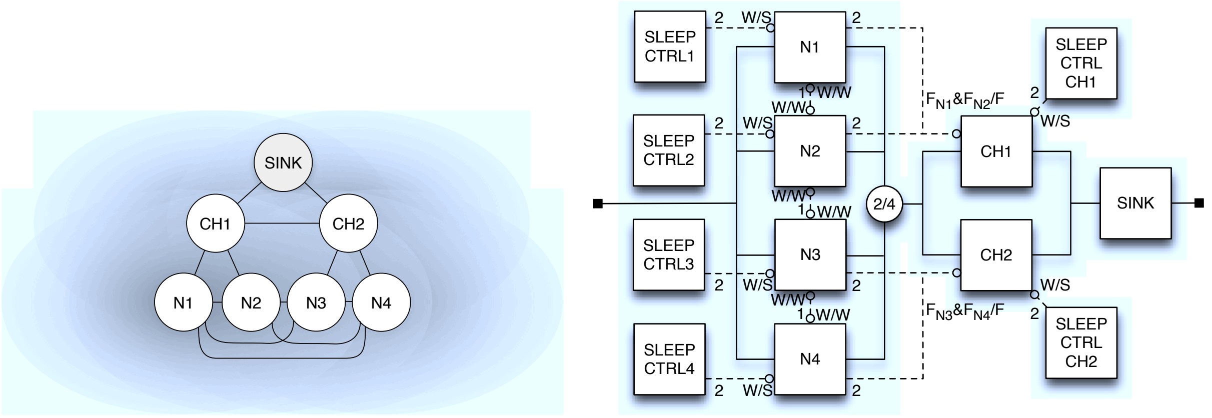
(b)

Fig. 8: A 4-node WSN all-to-all mesh topology (a) and corresponding DRBD (b).

a) All-to-all: In the all-to-all mesh topology of Fig. 8a all the cluster heads and nodes are connected each other thus allowing the other nodes to directly reach any WSN cluster heads. The resulting DRBD model shown in Fig. 8b is similar to the one of Fig. 7b. The only difference is on the common cause failure among cluster heads and nodes that, due to the redundant connections introduced in the all-to-all mesh topology, are not present in the DRBD model of Fig. 8b since new alternative paths are possible.

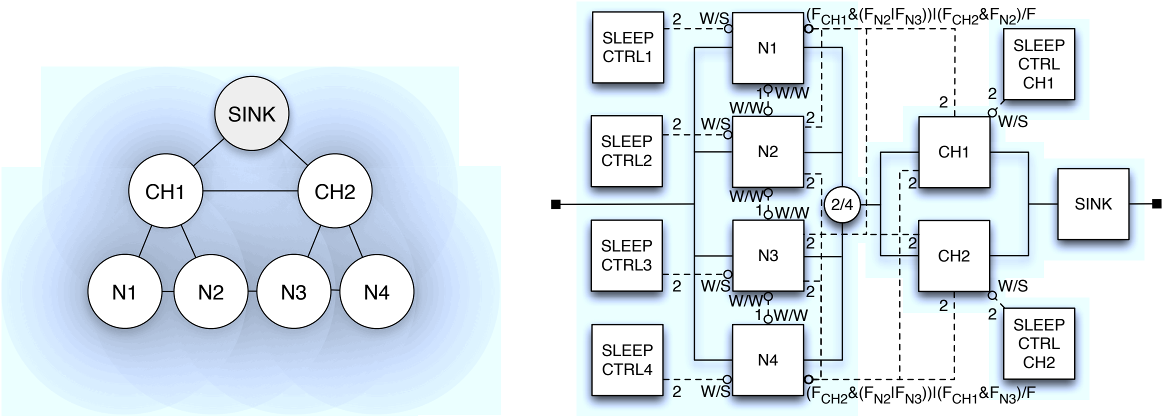
b) Fully connected: In the fully connected mesh topology of Fig. 9a all the nodes are connected each other thus allowing the other nodes to indirectly reach any WSN cluster heads when at least one node of the other cluster is operating. Otherwise, if both nodes of a cluster are failed, the corresponding cluster head cannot be reached by the nodes belonging to the other cluster. Thus, in the resulting DRBD model shown in Fig. 9b we have to introduce a specific dependency in order to model such restriction: if both $N1$ and $N2$ (as well as for $N3$ and $N4$) fail the corresponding cluster head $CH1$ ($CH2$) have to fail.

c) Partially connected: In the partially connected mesh topology of Fig. 10a the nodes are connected to their neighbors. Such topology can be considered a trade-off between the cluster and the fully connected mesh one. More



(a) (b)

Fig. 9: A 4-node WSN fully connected mesh topology (a) and corresponding DRBD (b).



(a) (b)

Fig. 10: A 4-node WSN partially connected mesh topology (a) and corresponding DRBD (b).

specifically, nodes N2 and N3 become bridges for the corresponding cluster allowing, in case a cluster head fails, to reach the other cluster head. Of course, the redundancy thus introduced is lower that the one of fully connected mesh.

Such specific feature has to be reported into the DRBD model, shown in Fig. 10b. In other words it is necessary to avoid some specific path-sets that are instead allowed in the previous configuration. In particular, if a cluster head fails, in order the WSN is reliable the other cluster head and the two corresponding nodes (N1 and N2 for CH1, N3 and N4 for CH2) have to be reliable, as in the cluster configuration. Moreover, the system is still reliable if N2 and N3 are both reliable. Such conditions are modeled into the DRBD of Fig. 10b by the two F/F dependencies with targets N1 and N4. These have been translated into logical conditions disabling the two nodes when the corresponding cluster head is failed and one of the bridge node (N2 or N3) are failed ($F_{CH}\&(F_{N2}|F_{N3})$), or if the other cluster head is failed and the other node of the cluster is down ($F_{CH1}\&F_{N3}$ and $F_{CH2}\&F_{N2}$).

C. Discussion and Motivations

The choice of DRBD is motivated by the limits of existing notations such as the DFT one. In fact, they do not allow to properly represent such dynamic-dependent behaviors. Specifically concerning the WSN models, the first modeling lack is in the "dependency composition": how to properly represent interferences involving two or more nodes/components? For example, composing DFT dynamic gates could not be an adequate solution. Indeed, it is necessary to specify what happens in case two or more "conflicting" dependencies such as the F/F dependencies related to the cluster head failures and the W/W ones modeling load sharing in the DRBD of Fig. 7, 8, 9 and 10, generating conflicts on the nodes.

To this purpose, DRBD provide a priority mechanism based on the connection priority to characterize a dependency, while DFT and other dynamic reliability notations do not take into account the problem. Moreover, as discussed above, in case of load sharing we assume, starting from literature, that the reliability function of a component/node in load sharing depends on how many components share the load. Thus, it is necessary to specify the effects of such phenomenon in terms of reliability dependencies, by varying the dependent component reliability according to the number of involved components. Such specific kind of dependency is neither considered nor represented in DFT as well as in other notations, while DRBD identify and classify it as *cooperating/overlapping* dependency, analytically characterized through merge functions as discussed above.

Last but not least, to the best of our knowledge dynamic reliability analysis techniques do not adequately consider and implement any conservation of reliability principle or similar concepts to deal with changes in reliability distributions of the components due to dependencies or interferences triggers. An in depth comparison among DFT and DRBD is provided in [32].

VI. NUMERICAL EXAMPLE

In order to show the capabilities of DRBD in WSN reliability evaluation, in this section we provide some numerical results obtained by evaluating the models proposed and discussed in Section V-B.

Parameters ***Mode***	c_0 - Initial Charge (mAh)	I - Discharge Current (mA)	t_B - Discharge Time (h)
Active	5000	100	61.56
Sleep	5000	3.4	4993

TABLE I: Parameters of a WSN star node in both active and sleep operating modes.

In such evaluation, we assumed that the nodes are identically distributed i.e., they are characterized by the same time-to-failure distribution function. Since from eq. (1) the reliability is expressed in terms of the battery discharge function $c(t)$, the resulting WSN reliability function is always a deterministic distribution, centred at discharge time t_B. Let us assume a non-linear discharge process for the battery in a node operating mode, more specifically following the Peukert law i.e.,

$$c(t) = c_0 - I \cdot H \cdot \left(\frac{t}{H}\right)^{(1/\eta)}$$

where H is the *hour rating*, I the *discharge current*, and η is the *Peukert's exponent or constant*. Moreover, we also assume that two alkaline batteries (AA/R6) supply the WSN node power, with $H = 25h$, $\eta = 1.3$ and initial capacity $c_0 = 2500mAh$ each, globally $c_0 = 5000mAh$. In this way, based on real values, the parameters reported in Table I are specified and used in the analyses.

In order to quantify the effects, the impact of interferences, it is necessary to fix the value of the interference parameter α of eq. (2). Considering the interferences not so frequent, we can choose a value in the range [0,1], for example a good one could be $\alpha = 0.5$.

More specifically, in the following we first evaluate the three example of WSN topologies above discussed, as reported in subsection VI-A, and therefore we further investigate the WSN star topology by performing a parametric analysis varying the duty cycle, as reported in subsection VI-B. The evaluations have been performed by mapping the DRBD into the corresponding Petri nets as specified in [10], [9], applying the technique proposed in [7], and therefore evaluating the obtained models by the WebSPN solution engine [33].

A. Topology comparison

The three example of WSN topologies above discussed have been analyzed starting from the values reported in Table I and a duty cycle $DC = 6\%$ over a whole sleep/wake-up period of 100 s. In this way we are able to make a comparative analysis of their reliability, providing information that could be useful in the WSN design, driving the topology selection.

The results thus obtained, expressed in terms of mean time to failures ($MTTF = \int_{t=0}^{\infty} R(t)dt$) of the topologies of Fig. 6, 7, 9 and 10 are reported in Table II.

Topology	**Star**	**Cluster**	**All-to-All Mesh**	**Fully-C. Mesh**	**Partially-C. Mesh**
No Int.	4902	4826	4877	4870	4855
With Int.	4779	4662	4770	4747	4713

TABLE II: MTTF (in hours) of the three topologies evaluated, without and with interferences.

Such results highlight the fact that, as expected, the star topology is the most reliable topology among the ones examined. But, on the other hand, as discussed above, the main drawback of such topology is the limited coverage area, restriction that can be relaxed by considering cluster and mesh topologies. Between these two latter topologies, the mesh one provides higher reliability guarantees, since they implement greater redundancy on links than cluster topologies.

Another aspect that could be observed by the obtained results is that the impact of interference is significant for all the topologies. In particular star topologies are sensitive to interferences, since the impact on the WSN reliability can be quantified in about the 3.4% of loss of MTTF against the one obtained considering no interferences. In the other two cases the impact of interferences is lower and the obtained values are quite similar (2.2% cluster, 2.5% all-to-all mesh).

Such results highlight that the impact of interferences in the overall WSN topology, in the specific example, can be quantified in the percentage range of [2.2,3.4] %. In several cases and applications it can be considered insignificant and can be therefore neglected without any practical consequence. However, the importance of knowing that the impact of interference is more or less significant is a relevant achievement of our work, that could be used in the WSN design and deployment in order to evaluate whether interferences have to be taken into account or not.

B. Star topology parametric analysis

Starting from the values of Table I, we have further investigated the reliability of the star topology example of Fig. 6. implemented parametric evaluations by fixing the whole sleep/wake-up period or the beacon interval to 100 s, varying the duty cycle DC in its range $[0, 1]$.

The MTTF results thus obtained are shown in Fig. 11. In the experiments we compared, as above, the model that does not take into account interferences against the same model with interferences.

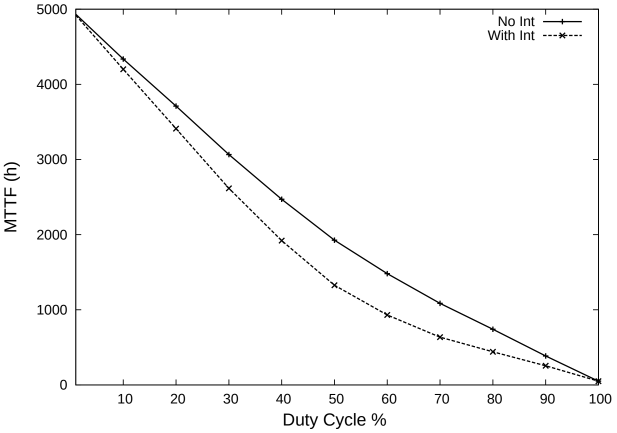


Fig. 11: MTTF of the 4-nodes star WSN by varying the duty cycle.

Such results highlight the fact that, the reliability of the whole WSN strongly depends on the duty cycle of its nodes. Moreover, since we considered a non-linear discharge process, both the trends non-linearly decrease by increasing the failure rate, but they are sub-linear. Such difference is particularly clear in case the interferences are considered. In fact, both trends start from the value of approximately 5000 hours ($DC = 0$), that corresponds to the condition in which all the nodes of the WSN are never activated and therefore are always in the sleep mode, and both terminate at approximately 61 hours ($DC = 1$), corresponding to the condition in which the WSN nodes never go in sleep or are always active. But, the MTTF obtained in case of $0 < DC < 1$ are not proportional to such values, fact that can be related to the (non-linear) type of discharge process taken into account, mitigated by the 2 out of 4 redundancy policy considered.

VII. FINAL REMARKS

This paper investigates the evaluation of the reliability of WSN applying a system reliability point of view. The investigation is split into two parts: the former focuses at node level, the latter instead focuses at network level. At node level the behaviours identified are the sleep/wake-up standby policies and interferences, that can be both characterized as dynamic aspects. At network level the structural reliability relationships are instead characterized as static.

The main contribution of the paper is to consider interferences and sleep/wake-up policies relaxing the assumption of exponential time-to-failure distribution. In such contexts it is not possible to recur to Markov models to adequately represent the battery discharge process since such models do not-linearly depend on time. The issue of taking into account interference in Markovian reliability problems has been adequately addressed in the specific literature, as discussed in Section II. This is definitely simpler than non-Markovian reliability problems, since Markov models and processes assume that the system is "without memory". In reliability terms this means that components do not wear out since they do not age according to the memory-less property of Markov models. On the other hand, in non-Markovian environments it is necessary to adequately take into account the component aging process, focusing on, in particular, what happens when a component change distribution. We faced this aspect in DRBD by applying the conservation of reliability principle as stated in [34], [35]. Another important aspect to consider is how the interference effects are merged when two or more of them affect a component/node simultaneously. For such kind of interferences it is necessary to adequately define how the interference effects have to be merged in order to specify the component reliability. The solution proposed is summarized by the merge function of eq. (2), applied in particular to model the WSN nodes' load sharing. To the best of our knowledge, this is the first attempt to consider interferences in non-Markovian environments addressing such specific problems.

Thus, in this paper we propose DRBD as an effective solution for the modeling and the evaluation of WSN, since DRBD allows to model both static and dynamic reliability aspects. In particular, starting from DRBD, the proposed approach firstly characterizes the dynamic reliability aspects and behaviors of a WSN at node level, therefore takes into account the network topology. In this way we have represented the three most important WSN topologies: star, cluster and mesh. We have also applied such approach to the evaluation of some specific examples of the different topologies, considering WSN composed of the same number of sensing nodes in order to compare their reliability. The results obtained confirm that, in the specific cases considered, the star topology is more reliable than the others but, on the other hand, it is also more sensitive to interference. Moreover, by further investigation on the star topology taken as example we have also clearly observed the impact of the non-linear discharge process on the WSN by varying the duty cycle.

An in depth study of the technique scalability on the WSN complexity is currently work in progress.

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