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Modeling Wireless Sensor Networks Using a Collaborative Graph-based Model

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Abstract: In several application scenarios, like the case of structural monitoring, it is important to model and represent the Wireless Sensor Networks (WSN) to be deployed. To model the components and properties of entire WSN types of collaboration in WSNs, we have created the Collaborative Wireless Sensor Networks (CWSN) model. This model also models the different types of collaboration that occur in a WSN. Our main goal is to provide a theoretical mathematical foundation that can model and analyze WSNs. Our approach is based on graph theory and propositional logic. The main contribution of this paper is applying the CWSN model to describe and represent a WSN. The use of the CWSN model brings several advantages, such as enabling the graphical representation of the state of the network and of several important properties: 1) the network topology; 2) the transmission between nodes considering a multi-hop communication; 3) the transmission hierarchy; 4) the evolution of the networks through a succession of graphs; and so on. *Copyright © 2015 IFSA Publishing, S. L.*

Keywords: Wireless sensor networks, Cluster, Graphs, Communication, Classical proposition logic, Network modeling.

1. Introduction

WSNs are a special case of wireless ad hoc networks, but characterized by specific constraints. Besides energy restrictions, sensor nodes suffer from other resource limitations: they have reduced memory and processing capabilities; and, due to short transmission range, nodes can only communicate locally, with a certain number of local neighbors [1-4]. In many cases, these networks are subject to highly dynamic conditions, caused by nodes' mobility, hardware failures, lack of battery, or other factors. To overcome these limitations, nodes have to collaborate in order to accomplish their tasks: sensing, signal processing, computing, routing, localization, security, etc. Therefore, WSNs are, by nature, collaborative networks [5].

There are quite a few works in the literature concerning collaboration in WSNs; however, they only focus a specific type of collaboration, which is associated with the accomplishment of a specific task. In [6], we proposed a formal and hierarchical model of cooperative work, the Collaborative Wireless Sensor Networks (CWSN) model, which is designed specifically for WSNs. It allows not only the modeling of collaborative work (based in CSCW

- Computer Supported Cooperative Work [7] - concepts), but also the modeling and visual representation of all the entities that can compose a WSN, as well as its properties. Moreover, CWSN is a generic model since it can be applied to heterogeneous networks. We have used first-order logic to formalize and describe the proposed model. We further employ graph-theory to describe how communication occurs within a cluster. This formal description of clusters' communication is based on directed graphs; nodes are labeled with the signal ±, respectively indicating if a node is active or not [6].

In this paper, we focus on using the graphical representation of the CSWN model to represent the state of the network and its properties. This graphical representation allows the user to comprehend what is occurring in a certain moment of the WSN lifetime, by easily visualizing the communication interactions, the state of the nodes (active or not), the state of the links, etc. This will allow enriching the proposed model and giving the user a better understanding of the components and the state of the WSN as well, through a more complete visual representation of the WSN. This is the main contribution of this paper.

This paper is organized as follows. In Section 2, we briefly describe the related work. In Section 3, the CWSN model and its entities are briefly presented. Then, a comparison between CWSN and other models is presented. The advantages of the model are, also, outlined. Section 4 presents the SAVER project, an application example of our model. Section 5 provides some conclusions and future work perspectives.

2. Related Works

There are several works that try to model some aspects of WSNs. We have observed that the great majority of works focus on modeling of connectivity or mobility problems, or even on both problems. Moreover, we have identified other modeling concerns, such as: communication models, interference models, data aggregation models, coverage models, and signal processing models. On the contrary, the CWSN model intends to model a whole WSN, i.e., it tries to consider the most complete set possible of entities that can exist in a WSN, and their respective attributes.

Regarding the works focusing collaboration in WSNs, the great majority of them covers a specific type of collaboration, which is associated with the accomplishment of a certain task, such as: signal processing [8], sensing [9], computing [10], routing [11], localization [12], security [13], task scheduling [14], heuristics [15], calibration [16], resource allocation [17], time synchronization [18], transmission [19], etc., and also works concerning collaboration between wireless sensor nodes and other kind of devices (heterogeneous groupware collaboration) [20-21] to support some specific applications (for example, collaboration between sensor nodes and PDAs, in a fire fighting scenario).

According to the literature, the only work that presents a model for collaborative work, in sensor networks, was proposed by Liu, *et al.* [22]. It is the Sensor Networks Supported Cooperative Work (SNSCW) model, a hierarchical model that essentially divides cooperation in sensor networks in two layers; the first one relates to cooperation between humans and sensor nodes; the second one relates to cooperation between the sensor nodes. This model was designed for sensor networks.

However, the SNSCW model only allows the modeling of collaboration itself. On the contrary, the CWSN model, which has been presented in [6], is a formal model that was created specifically to describe WSNs. However, the CWSN model allows not only the modeling of collaborative work (based in CSCW concepts), but also the modeling, formalization and visual representation of the entities that can constitute a WSN (different types of nodes, clusters, relationships, sessions, obstacles, etc.), as well as its attributes. Moreover, it allows the representation of the WSN's hierarchy and of the network evolution.

The CWSN model formalizes the most significant properties of each entity through first-order logic. Even though the CWSN model is a graph-based model, it includes other objects [6] in order to make the modeling of the various entities of a WSN possible. This is of paramount importance to completely represent a WSN.

WSNs are extremely dynamic systems, both in the sense that their characteristics change over their lifetime and for the fact that sensor networks' technology (hardware and software) is subject to fast changes. To overcome this issue, the CWSN model can be updated or extended, through the introduction of new entities and/or new attributes. Therefore, another key point of this model is its scalability, since it can easily evolve.

3. The CWSN Model

The CWSN model is a formal model of collaborative work that was specifically created to describe WSNs. This model allows the representation of the entities (different types of nodes, clusters, relationships, sessions, obstacles, etc.) and properties of a WSN, of its hierarchy, and of the network evolution; therefore, it allows not only the modeling of collaborative work (based in CSCW concepts), but also the modeling, formalization and visual representation of a whole WSN.

The CWSN model formalizes all the properties of each entity through first-order logic. Also, CWSN is a graph-based model; however, it includes other objects in order to make possible the modeling and visual representation of all the entities that can compose a WSN. This is of paramount importance to completely represent a WSN.

3.1. CWSN Model Definitions

We define entities as all the components that might exist in a WSN. The symbol, the concept and the description of all the entities included in the proposed model are illustrated in Table 1.

A WSN can have different types of nodes: ordinary wireless *sensor nodes*, anchor nodes, one or more sink nodes (also known as base stations) and a gateway. The *sink node* and the *anchor node* are wireless sensor nodes with special functions.

A *cluster* is a group of nodes, created according to: geographical area, type of sensor nodes, type of phenomenon, task to be performed, etc., providing the WSN with a hierarchical structure. If nodes are grouped in clusters, one of the members of each cluster becomes the cluster head (there is only one cluster head per cluster). In this case, all nodes in the cluster have to send collected data to the cluster head (for instance, the more powerful node or the router, in case of a ZigBee-based WSN), which, in turn, is responsible for sending data to a sink node.

If two nodes collaborate, there is a *relationship* between them. Associated with a relationship there is always an exchange of data, which corresponds to the *data flow* entity. Collected data (temperature, humidity, light, etc.) can be sent to other nodes using one or more types of signals (radio, ultrasound, acoustical, etc.).

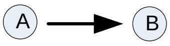
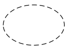
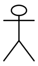
Obstacles are objects (for, e.g., building, tree, rock, etc.) that may obstruct the line-of-sight between two or more nodes, not allowing for direct communication between them. So, they can influence the relationships created.

The *user* is the entity who interacts with the WSN, defining the application, querying the network, visualizing data, customizing the work of the sensor nodes, etc.

Several collaborative *sessions* can be established when monitoring a WSN, and they can exist simultaneously or not. Basically, new sessions may be established based on new queries a user makes on the WSN.

And, last but not least, as the *battery* is the most critical resource of a sensor node, it is really important that the user knows the state of the battery of each sensor. That is why the battery is also an entity of our model.

Table 1. Definition of the entities can constitute a Wireless Sensor Network.

Symbol	Concept	Description
	Sensor node	Nodes can be either stationary or mobile. Also, they can be in one of three possible states: active, sleep mode (in order to save energy), or inactive.
	Sink node/ Base Station	Node to which data collected by ordinary nodes is sent; being responsible to send data to the gateway. If there is only one sink node, all data collected by sensor nodes has to be sent to it. Otherwise, data may be sent to any sink node and, in this case, sink nodes must be able to communicate to each other.
	Anchor node	Node with known localization, which support the other sensor nodes in the localization process
	Cluster	Group of nodes, created according to: geographical area, type of sensor, type of phenomenon, task, etc.
	Cluster Head	Sensor node to whom all sensor nodes in the cluster send the collected data; it is responsible for sending the received data to the Sink node.
	Relationship	The arrow represents a relationship between nodes A and B. It also represents and adjacency relation between nodes A and B; nodes A and B are neighbors. A relationship can be established based on: localization, phenomenon, type of sensor node, etc.
	Data flow	This label identifies both the type of signal being used (radio frequency, ultrasound, acoustical or light) and the type of data being transmitted between nodes (temperature, humidity, light, sound, video, internal voltage, etc.).
	Gateway	Device responsible to send the data to the user, through the Internet or satellite.
	Obstacle	An object (building, tree, rock, etc.) which may obstruct the line-of-sight between two or more nodes; depending on the type of signal that is being used by nodes (radio frequency, optical, acoustical, etc.), the obstacles may even not allow for communication between nodes.
	Session	In a certain moment, there may be several collaborative sessions in a WSN. A session can be established based on the objective (type of phenomenon to monitor, geographical area to monitor, etc.) of the WSN.
	Battery	It represents the percentage of the sensor node's remaining battery.
	User	Person that interacts with the WSN, querying the network, visualizing data, etc. The user customizes the work of the sensor nodes; the data collected by sensor nodes is used by the users' application.

In this section, we formalize the model's entities and their main properties, using both first-order logic and graph theory.

1) Definitions: We can formulate the sensor network as a graph G(V,E). V (vertices) represents the set of sensor nodes, and E (edges) describes the adjacency relation between nodes. That is, for two nodes $u, v \in V$:

$(u, v) \in E$, if, and only if, v is adjacent to u. If a node u is within a node v's transmission range, we say that u is adjacent to v, or equivalently, that u is a neighbor of v. In the absence of interference, this relation is typically symmetric (or bidirectional), i.e., if a node u can hear a node v, also v can hear u.

An arrow between two nodes represents a relationship between them. A relationship can be established based on: localization, phenomenon, type of sensor node, etc. The arrow represents a producer-consumer relationship. Let us consider two nodes A and B; the arrow $\textcircled{A} \rightarrow \textcircled{B}$ means that node A transmits data to node B. So, node B consumes information from node A. The transmission of data between both nodes follows the format TypeOfSignal.Data ($\xrightarrow{\{TypeOfSignal.Data\}}$), verifying the consumer-producer property.

So, according to the specifications of the CWSN model, a WSN can be represented using labeled and directed graphs; the labels are associated to the edges and are designated by data flow. TypeOfSignal.Data identifies these labels. The labels inform the user about the type of signal that is being used by the sensor nodes for transmitting data (for, e.g., radio frequency, ultrasounds, acoustical, etc.), and about the type of data that is being collected and sent to the sink node (for, e.g., temperature, humidity, light, acceleration, etc.). These labels are important because they allow the user to become more aware of the state and the behavior of the WSN, since the labels add information that goes beyond the mere representation of the communication interactions between nodes.

Let's represent the total number of sensor nodes that constitute the WSN by Nr, with $N = \{1, 2, \ldots, Nr\}$ and a wireless sensor node by N_i, with $i \in N$. The WSN has a limited lifetime, which can vary from some hours to several months or years. Let us denote the lifetime of the network (in seconds) by LT, with $T = \{1, 2, \ldots, LT\}$, and the j^{th} second of life of the network by t_j, with $j \in T$.

2) Sensor Node (N_i): A sensor node (N_i) is defined by:

$N_i = \{ID, TS, CM, CT, R, PS, L, TM, S, PD, CN\}$

Table 2 defines and formalizes the properties that are important to identify a sensor node (Ni). This Table serves as an example for the type of formalization that has been proposed for the remaining entities, presenting a formal description of their most important properties [6].

3) Sink Node (S_K): The sink node is the node to which data collected by ordinary sensor nodes is sent. It is responsible for sending data to the gateway being the only node that can do it, what verifies the flow control property. Regarding mobility, two cases must be distinguished: the Stationary Sink Node (StS_K), with the localization of the sink being well-known and independent of time; and the Mobile Sink Node (MbS_K), where the localization of the sink node varies as it moves along the WSN.

4) Anchor Node (A): If the localization (L) of wireless sensor nodes is unknown (usually, due to an ad hoc deployment), it may be necessary to have some anchor nodes to help these sensor nodes to determine their own localization. So, an anchor node differs from a sensor node because its localization is always well known. This can be achieved either by equipping the anchor node with a GPS receiver or by manually configuring its position prior to deployment. Regarding mobility, an anchor node (A) can be:

- Stationary (`StA`): In this case: TM (`StA`) = `St`
- Mobile (`MbA`). In this case: TM (`MbA`) = `{ContMb, Des}` or TM (`MbA`) = `{OcMb, Des}`

5) Network (WSN): So, a WSN can be defined by the following properties:

$WSN = \{To, M, H, Nr, A, C, D, Hi, NS_K, NA, NC, NO, LT\}$.

6) Session (Se_i): A session is the essential unit of a collaborative activity, which can be created based on different queries posed by the user. Depending on the WSN specific application, sessions can take place in parallel or in sequence; or they can be synchronous or asynchronous. Thus, in a certain moment, there may be several collaborative sessions in a WSN. A session (Se_i) can also be formulated as a sub graph, g, of the WSN, with $g(V,E) \subseteq G(V, E)$. Accordingly, some properties of the entities network and the sensor node are inherited.. Similarly to a sensor node (N_i), a session (Se_i) can be in one of two states: Active (Ac), or Inactive (In) when its objective is fulfilled. So: $S(Sei) = Ac$ or $S(Sei) = In$.

Besides, similarly to the entity network, each session can have a group of active sensor nodes, a group of inactive sensor nodes and a group of relationships and data flows. So, a session (Sei) is defined by the following properties:

$Se_i = \{Se_{iID}, SeObj, S, DTx, SeTLife, To, M, H, A, C, D, Hi, Nr, NS_K, NA, NC, NO\}$.

Note that the topology (To) has the same definition as in Table 2; however, considering a specific instant of time, the topology of the session (Se_i) may be different from the topology of the WSN.

Also, considering the number of nodes, number of anchor nodes, number of sink nodes, number of clusters and number of obstacles, note that:

Nr (Se_i) ≤ Nr (WSN), NA (Se_i) ≤ NA (WSN), NSK (Se_i) ≤ NSK (WSN), NC (Se_i) ≤ NC (WSN), NO (Se_i) ≤ NO (WSN), and SeTLife (WSN) ≤ SeTLife (Se_i)

7) Cluster (C): If a clustering algorithm is applied [23], clusters will be formed. Sensor nodes are grouped into clusters, mainly to support scalability (for managing a high number of nodes). But, besides supporting scalability, clustering can have several different objectives, such as: load balancing, fault tolerance, network connectivity, maximal network longevity, etc. Each cluster has a leader, the cluster head (CH). So, a cluster (C) is defined by:

C = {C_{ID}, CH, Stb, NrC, IaC-To, IeCH-Con, CMet}.

Even though clustering is influenced by the network and link layer protocols, some attributes can be identified.

8) Cluster Head (CH): The cluster head (CH) can be elected by the sensors in a cluster or pre-assigned by the network designer. Also, CHs may be the richest nodes in resources of the whole network. So, a cluster head (CH) is defined by [23]:

CH = {CH_{ID}, TM, TN, Ro}.

3.2. Main Properties Represented by the CWSN Model

The CWSN enables the graphical representation of several important properties, like nodes' mobility, connectivity and communication, network heterogeneity and stability, network coverage, consumer-producer and flow control, as well as the graphical representation of other important aspects, like, the occurrence of failures, the network topology, the established routing paths, or the communication modality used by nodes and the type of sensed data. However, some aspects like signal interference was not considered in the CWSN model.

The representation of some of these network properties, like mobility of nodes or topology changes, is possible through the representation of the network evolution. In other words, the model represents a screenshot of a WSN in a specific moment of time. As time goes by, several aspects of a particular WSN can change:

1) The state of the nodes can change;
2) New nodes can be deployed;
3) The topology can suffer modifications;
4) New clusters can be created;
5) New obstacles can appear; etc. In the CWSN model, these network changes are naturally represented through a succession of figures as exemplified in Fig. 1.

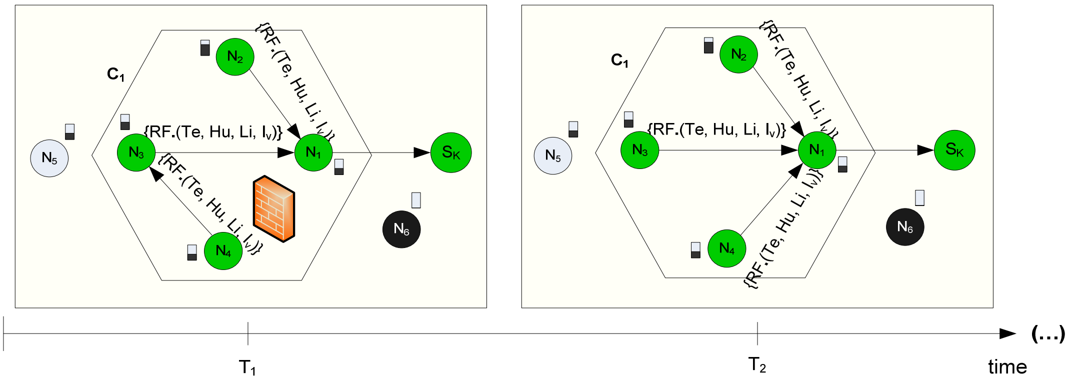


Fig. 1. Modeling a change in the network topology, applying the CWSN Model.

Fig. 1 represents a modification in the topology of the network caused by the elimination of an obstacle. The obstacle was located between nodes N_4 and N_1, impeding direct communication between these two nodes. For some reason (the obstacle may be static, like a tree or building, or it may move, like an animal or a car), the obstacle has disappeared. Consequently, connectivity and, therefore, communication has been established between the referred nodes.

The *consumer-producer* is another property that can also be deduced from the CWSN model, and it is denoted through the use of directed graphs, i.e., through the direction of the relationship between nodes. Formally, the *consumer-producer* property can be described as follows:

Considering that the WSN is represented as a graph constituted by vertices (nodes) and edges (relationships), and that the vertices use these edges to transmit data, with a set of data being represented by *Da*, then a WSN can be described as:

$$G_D(V_D, E_D),$$

where V_D represents the group of Nr participant nodes (Ni), and

$$E_D = (N_{i,prod}, Da, N_{j,cons}),$$

with i ≠ j, and *Da* is the set of data that is shared by the producer (Nprod) and the consumer nodes (Ncons).

Table 2. Definition of the properties of the entity a Sensor Node (Ni).

○	**Properties**	**Description / Formalization**
Sensor Node (N_i)	Identifier (I_D)	Each sensor node has a unique identifier (I_D) I_D (N_i) = i , i ∈ ℕ
	Types of sensors (TS)	A sensor node (N_i) can have several types of sensors, each one measuring a different phenomenon: light (Li), temperature (Te), humidity (Hu), sound (Sd), internal voltage (Iv), acceleration (Ac), pressure (Pr), vibration (Vb), received signal strength indicator (RSSI), etc. So, TS (N_i) ⊆ {Li, Te, Hu, Sd, Iv, Ac, Pr, Vb, RSSI, ...}
	Communication modality (CM)	A number of communication modalities can be used, such as: radio (RF), light (Li), ultrasound (US), acoustical (Ac), optical (Opt), hybrid (Hy). So, CM (Ni) ⊆ {RF, Li, US, Ac, Opt, Hy}
	Communication Technology (CT)	A sensor node (N_i) can use different communication technologies. So far, three technologies have been proposed: ZigBee (ZB), which corresponds to IEEE 802.15.4; Bluetooth (BT); IEEE 802.11 (WiFi). So, CT (Ni) ⊆ {ZB, BT, WiFi}
	Transmission Range (R)	Let P_t be the nominal transmission power of a node. P_R; j ← i is the received power of a signal propagated from node i to node j. A received power P_R; j ← i above a given threshold P_{th} will provide sufficient SNR (*Signal to Noise Ratio*) in the receiver to decode the transmission. The nominal transmission range for successful communication can be defined as [19]: $R = P_t/P_{th}$ Note that due to the instability in the transmission range, the area a wireless sensor node can reach is not necessarily a circle and the range can vary between $r=(1-\varepsilon)$. R and R, $\varepsilon>0$ [19].
	Power Supply (PS)	Energy can be supplied by batteries (that are, usually, of very limited capacity), solar cells or an external and unlimited power supply (only possible if nodes are stationary and in indoor applications). ▪ Battery (B); ▪ Solar cells (SC); ▪ External and unlimited power supply (VDC); ▪ Hybrid (Hy) – for, e.g., battery and solar cells; ▪ Etc. PS (StS_K) ⊆ {B, SC, VDC, Hy, etc.} However, the great majority of sensor nodes are equipped with batteries. The lifetime of a sensor node (N_i) is limited by its battery, depending on its capacity and type. The battery can be defined by: ▪ Type of battery: T_B, with T_B (N_i) ∈ {lithium, alkaline, li-ion, AA, external power supply, solar cells, electromagnetic and piezoelectric transducers, etc.} ▪ Capacity (voltage): C_B (N_i) [V] ▪ Remaining capacity at time t_j: P_{BNi} (t_j) [%] BNi (tj) = {TB (Ni), CB (Ni), PBNi (tj)}
	Localization (L)	Let L_{Ni} (t_j), with i ∈ N and j ∈ T , denote the location of node N_i at time t_j. The type of deployment affects important properties of the network (node density, node locations, etc.). The deployment of sensor nodes may be: ▪ Random (ad hoc deployment, for, e.g. dropped by an aircraft). In this case, the localization of a node is unknown: L_{Ni} (t_j) = (x, y, z), where x, y, z ∈ ℝ are unknown. ▪ Manual: sensor nodes are deployed in pre-determined positions. In this case, the localization of a node is well-known: L_{Ni} (t_j) = (a, b, c), where a, b, c ∈ ℝ are known.
	Product Description (PD)	Alphanumeric that identifies the brand and the model of the sensor node. PD (Ni) = {Brand (Ni), Model (Ni)}
	Consumer Node (CN)	Often referred to as parent node, is the node to which the sensor node N_i is sending data at time t_j. Considering for example a relationship between nodes A and B; if node A is transmitting to node B, then B is the consumer node since it is receiving the data.
	Type of Mobility (TM)	A sensor node (Ni) can be: ▪ Stationary (St): $L_{Ni}(t_1) = L_{Ni}(t_2) = \ldots = L_{Ni}(t_{LT})$ ▪ Mobile (Mb): The period of mobility can be occasional or continuous: Occasional (Oc), when long periods of immobility occur: $\exists j, l \in T : L_{Ni}(t_j) \neq L_{Ni}(t_l)$, and $j \neq l \ \wedge \ \exists r, s \in T : L_{Ni}(r) = L_{Ni}(r+1) = \ldots = L_{Ni}(s)$, and $s >> r$ Continuous (Cont): $\forall j \in T \setminus \{LT\}\ L_{Ni}(t_{j+1}) \neq L_{Ni}(t_j)$ Mobility can still be classified in: ▪ Incidental (Inc), for, e.g., due to environmental influences ≈ Occasional ▪ Desired (Des), whether active or passive, which can be applied to any period of mobility (occasional or continuous). So, TM (Ni) ∈ {St, {OcMb, Inc}, {OcMb, Des}, {ContMb, Inc}, {ContMb, Des}}
	State (S)	Depending on its power mode, the node N_i can be in one of two states (S): ● Active (Ac): Node that is in the active state. Its color will depend on the cluster it belongs to, since each cluster will be represented by a different color. By default, the green color will be used. ○ Sleep Mode (Sm): Node that is in the sleep mode, in order to save energy. Colored in grey color. ● Inactive (In): Node that is damaged, or has some failure or has run out of energy. Colored in black color. So, S (Ni) ∈ {Ac, Sm, In}

For example, in Fig. 1, N_1 is the cluster head and, thus, the consumer node, whereas the remaining nodes of the cluster, namely N_2, N_3, and N_4, are the producer nodes. Similarly, the sink node is the consumer of all data produced in the WSN. Also, a cluster head consumes data from all the nodes of the cluster.

This property allows assuring that $G_D(V_D, E_D)$ is a connected graph, given that at least one relationship between two nodes exists.

Another property that can be inferred from the CWSN model is the *flow control* property. The sink node is the only node that can send data to the user. Therefore, all nodes have to send collected data to the sink node. Therefore, the sink node verifies *flow control* property; it controls the flow of data. This means that, regardless the considered moment in the whole lifetime of the WSN, only the participant sink node can send data to the user.

Similarly, if clustering is implemented, all the nodes that belong to the cluster have to send data to the cluster head, which in turn forwards data to the sink node (using other cluster heads, if necessary). Consequently, the cluster head verifies *flow control* property; it controls the flow of data.

Since both the sink node and the cluster head verify the *flow control* property, this property can formally be described as:

$E_D = (S_{k,prod}, Da, User_{cons})$ or $E_D = (CH_{prod}, Da, S_{k,cons})$,

where Da is the set of data that is shared by the producer (S_k or CH) and the consumer nodes ($User_{cons}$ or S_k).

Thus, the CWSN model also addresses some of the most important CSCW concepts but, more importantly, it addresses the analysis of temporal information. This can be used as an input for creating a real-time tool that allows visualization and representation of a WSN, as we have demonstrated in [25], where the CWSN model was translated into XML language, which was used as an input for the tool.

3.3. Comparing the CWSN Model with Other Models for WSNs

Table 3 allows a quick overview of the main differences between the CWSN model and other models that have been applied to model these networks.

The remaining state-of-the-art, models mostly address the modeling of a single issue of WSNs, addressing up to two issues (like mobility and connectivity) in the most complete modeling cases. Contrarily to these models, instead of focusing on modeling some specific problem of WSNs, the CWSN model is used to systematically describe and represent the features and properties of all the components that might constitute a WSN. So far, no other model has covered so many aspects of a WSN as the CWSN model does.

For example, unlike the SNSCW model [22], our model does not only model the cooperation within the network, but also the entire WSN. The CWSN model also allows the representation of the network hierarchy, from the collected data to the user (passing through the clusters, the session and the WSN). Moreover, the CWSN model is generic, in the sense that it can model heterogeneous networks and that it can be applied to any type of wireless sensors, (regardless its size, its hardware characteristics, the types of signals it can measure, etc.). It can also be applied to any WSN despite its specific application. So, it is possible to use all the entities defined in the model to represent a specific scenario of any application (monitoring a forest, a vineyard, a volcano, a museum, a natural catastrophe, etc.).

Besides, any changes that might occur on a certain application scenario (new collaborative sessions, new clusters, nodes moving, etc.) can be represented by a sequence of figures; hence, the CWSN model allows the representation of each state of the network and its evolution.

Regarding collaboration, the model includes some fundamental CSCW [7] concepts (for, e.g., session, relationship, data flow and groups) and properties (for, e.g., consumer-producer and flow control). Thus, analyzing Table 3, it is possible to conclude that the CWSN model presents important advantages over the state-of-the-art models presented in Section 2.

3.4. Contributions of the CWSN Model

WSNs are extremely dynamic systems, both in the sense that their characteristics change over their lifetime and for the fact that sensor networks' technology (hardware and software) is subject to fast changes. To overcome this issue, the CWSN model can be updated or extended, through the introduction of new entities and/or new properties. Therefore, another key point of this model is scalability, since it can easily evolve.

The CWSN model itself models the most important components of the WSN. As such, their advantages are:

- The CWSN model provides a grammar for formally modeling an entire WSN, i.e., all the entities that can exist in a WSN, and their respective attributes.
- It also allows to visually and graphically representing a whole WSN, including not only its entities, but a very important aspect to users and network managers, the network topology. Basically, the CWSN model provides a common framework for describing and representing any WSN.
- Moreover, the CWSN model allows representing the network hierarchy, from the collected data to the user, passing through the sensor nodes, the clusters, the sessions and, finally, the whole WSN.

- Besides, any changes that might occur on a certain application scenario (mobility of nodes, failure of nodes, topology changes, new collaborative sessions, new clusters, etc.) can be represented by a sequence of sub-graphs; hence, the CWSN model allows the representation of each state of the network and its evolution.

Furthermore, the CWSN model is generic, since it can model heterogeneous networks; it can be applied to any type of wireless sensor nodes (regardless their size, their hardware characteristics, the types of signals they can measure, etc.), and to describe and represent any WSN, despite of its specific application. So, it is possible to use all the entities defined in the model to represent a specific network scenario of any application (monitoring a forest, a vineyard, a volcano, a museum, a natural catastrophe, etc.).

4. The CWSN Model Applied to Structural Health Monitoring

The use of WSNs have brought several advantages in structural monitoring and the establishment of structural health compared to conventional methods where computers connected to accelerometers are used. In conventional methods, it is necessary to install cables through the structure, disturbing its normal operation and generating maintenance cost. Compared with conventional methods, WSNs provide the same functionality at a much lower price and a more flexible monitoring. Another problem is the high equipment and wiring installation and maintenance cost.

Table 3. Comparative analysis of the models created for WSNs.

Model	Modeling issues	Graph-based	CSCW concepts	Collaboration levels	Graphical representation of the WSN	Formal model
Kenniche and Ravelomananana (2010)	Topology	YES	NO	NO	YES (topology)	NO
SNSCW (Liu, *et al.*, 2006)	Cooperation	NO	YES	YES (two)	NO	YES
Wang (2011)	Coverage	no	no	no	no	Deployment and topology control
Bonaci, *et al.* (2010)	Behavior of the WSN under attack	yes	no	no	no	Network security
Wu and Chung (2009)	Sensing and Coverage	no	no	no	no	Deployment and topology control
Ni, *et al.* (2009)	Sensor faults	no	no	no	no	Fault detection
Wüchner, *et al.* (2010)	Performance	no	no	no	no	Evaluation of performance and energy efficiency
CWSN	**The whole WSN and collaboration hierarchy**	**YES**	**YES**	**YES (five)**	**YES (whole WSN)**	**YES**

The cost of a conventional system with a computer and a piezoelectric accelerometer is about USD 40000 per sampling point. The estimated cost of the proposed system, in this work is less than USD 200 per point. In WSNs no wiring is required, making installation and maintenance much easier and inexpensive. Moreover, the use of WSNs allows Structural Analysis of VulnerabilitiEs of buildings through wiReless sensor networks (SAVER) platform to be deployed and operate even if the building is in operation. It does not cause further visual impact due to its small size, low power consumption and installation flexibility. The advantage of structural health monitoring based on WSNs can be extended if the MEMS acceleration sensor type is used. The MEMS accelerometer is a silicon chip, which is very compact in size, low power consumption and cheap. Without MEMS, a small WSN, even low-power and low-cost accelerometer, would be degraded.

Thus, the SAVER platform will aim at gathering information to establish the vulnerability level of structural health of buildings. Such information will be used in decision making for both schemes and prevention programs, and for post-seismic evaluation.

The SAVER platform will be able to monitor and display information in real-time. It will determine from the implementation of several methods for estimating seismic response and damage detection, the level of structural vulnerability of buildings. In addition, our platform will offer several services that will notify users about potential risks of the structure through alarms, email and SMS. Besides, it will have a Web based monitoring platform and a mobile app for Android and I-Phone. Also, this platform will generate graphs, reports and statistics. Some preliminary results of the SAVER project was publish in [26].

The expected results, in SAVER project, intend to give the basis for the analysis of buildings and gather instrumental data that can be useful for decision-making of institutions and users that are responsible for infrastructure and buildings. Furthermore, in this project, we pretend to provide the necessary information to implement methods of vulnerability analysis and therefore, to estimate the seismic risk of buildings, such as hospitals or schools.

SAVER project will be validated in the building B (Fig. 2) of UPAEP University, located in Puebla city in México. This building is structured based on reinforced concrete rigid frames. Furthermore, it is regular in plan and consists of four levels with a height of 3.15 m each one, so it has a total height of 12.60 m. In the transversal direction, it has a bay of 10.50 m. In the longitudinal direction, the building has eight bays of 6 m each one, so that it has a total length of 48 m. The structural elements are composed of beams and columns. The beams, in transversal direction, have square cross section at all levels.

Fig. 2. Building B of the UPAEP University.

In the longitudinal direction at Level 1 and 4, they have variable prismatic section, while in Level 2 and 3 are rectangular. All columns in each level have variable hexagonal section. Floor system has 0.25 m thickness and is prefabricated. The building has masonry walls with 0.15 m thickness. This building was built in 1984. In recent studies, we have determined a high level of structural vulnerability. But, these studies were made using only three wired sensors. In order to obtain a better vulnerability estimation, we intend to instrument this building using the SAVER platform. The proposed topology for this building is shown in Fig. 3.

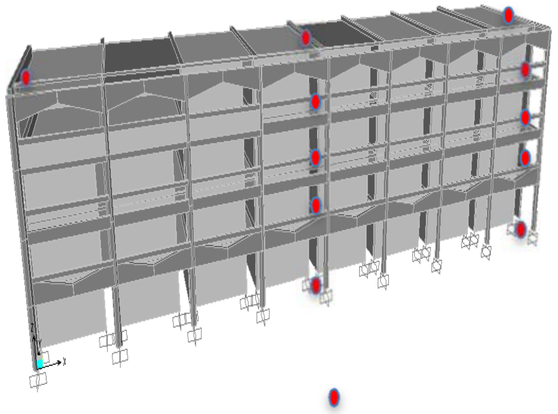


Fig. 3. Topology of the WSN installed in the Building B.

We are planning to install 12 sensor nodes. Each node has two sensors, a temperature sensor and an acceleration sensor. Using CWSN model, we can visualize the interaction among the sensors and their relationship.

The spatial distribution of the sensors is established from the geometry of each building. But it is necessary to deploy each sensor at least one in the geometric center of each level, and one sensor on the corner of the roof. If the longitudinal dimension of the building is large, it is suggested deploy some sensors in one border of the building. It is important to monitor also the ground response using a free field sensor.

Fig. 4 shows the WSN deployed in Building B, but represented using the entities proposed by the CWSN model.

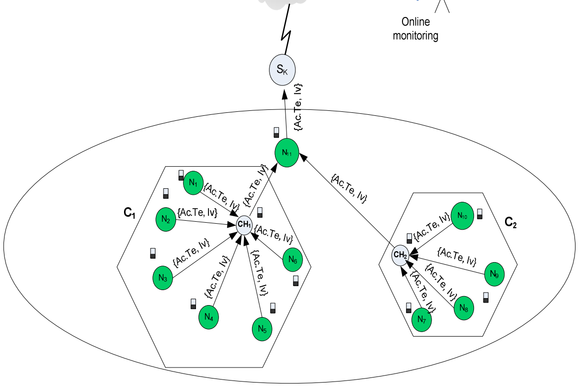


Fig. 4. Modeling Building B's WSN.

Basically, this representation clearly shows that only one session is established, but more importantly, it shows the structure of the WSN and the interactions that will take place between the different types of nodes that compose it. For instance, it shows that nodes are grouped in two clusters.

Using the CWSN model, it becomes evident the type of data collected by each node.

The problem to establish the structural health on buildings will be reduced if we use the CWSN model. The model can provide a tool for getting instrumental information about the structural properties, like acceleration on each storey as well as some structural dynamic parameters. If we use a sensor that can measure the acceleration (Ac) at each storey and considering that each sensor can provide the record of (Ac), in three orthogonal directions, respect to the building (longitudinal, transversal and vertical), the CWSN model can be implemented in order to estimate the structural vulnerability level. For this reason, we need to compute a parameter correlated with the lateral displacement and the structural damage.

The structural vulnerability level can be estimated using the algorithm presented in [26], where this level is associated with a damage parameter. The vulnerability can be estimated using a function, which considers the physical damage at any story and is defined as:

$$d(u) = 1 - \exp(-au^m) \tag{1}$$

where a and m are the parameters to be determined according with the structural system features (frame, walls, etc) and u is the local deformation of interest, normalized with respect to its peak value at failure (total loss). The damage function is obtained as function of the corresponding inter-story drift. In this way the parameter u is related to the lateral displacement. The lateral displacement u can be determined considering two criteria:

1) Using actual seismic records,
2) Using ambient vibration records.

The first approach is direct, because we use the record acceleration time history on different floors along the building. A double integration of the acceleration time-history can be used in order to obtain the response displacement. For this is necessary to apply a numerical procedure for integrating the corrected and filtered acceleration time-history, assuming that it has a linear variation between each time increment. For the velocity time-history this procedure is repeated in order to estimate the displacement time-history. The maximum inter-story drift can be determined by the following expression:

$$\psi_{\max j} = \left| \frac{u_{j+1}(\mathrm{t}) - \mathrm{u}_j(\mathrm{t})}{h_{j+1} - h_j} \right|, \tag{2}$$

where $\psi_{\max j}$ is the maximum inter-story drift, $u_j(t)$ is the lateral displacement at level "j" for a time t, and h_j is the vertical distance between each level.

The second approach considers several steps that are described in the follow. First, it is necessary to synchronize the signals with a common time reference and carry out the polarization procedure according to the sensor´s orientation and the reference system. The baseline correction of the original records also is needed. In order to eliminate the undesirable components of frequency a signal filtering procedure is recommended for this we can use a Butterworth. For the ambient vibration records in three directions we can apply the Fast Fourier Transform (FFT), in order to obtain the Amplitude Fourier Spectra. With this information we can estimate the transfer functions, the vibration periods and mode shapes. The vibration period and the mode shapes can be used for generating a Simplified Reference System (SRS) using the criteria proposed in [27]. The SRS has dynamic properties that represent the behaviour of the actual building, however is necessary introduce the corresponding transform response factors. These factors are also defined in [28]. In order to obtain the non-linear response of the SRS, in terms of lateral displacement, an adequate hysteretic model will be adopted. The non-linear responses can be related with a specified seismic scenario. In Fig. 5 the SRS model is shown, where m, k and c are the mass, stiffness and damping coefficients of the building, respectively. These parameters are correlated with the dynamic properties.

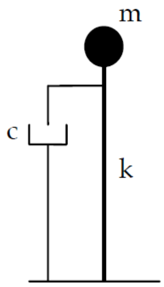


Fig. 5. SRS model.

In this implementation we can define the specific properties for each Sensor Node (Ni), for example, we can use three Types of sensors (TS): Ac, Te and lv; Communication modality (CM) can be defined as radio; for the Communication Technology (CT), we can use ZigBee (ZB); the Power Supply (PS) can be a Hybrid type (Hy); the Localization (L) can be defined as Manual.

In order to show the advantages of the SAVER platform, we present a structural vulnerability function for building B (Fig. 6). The vulnerability function describes the damage level d(Ψ)in terms of inter-storey drift d(Ψ). The values of damage are from 0 to 1. A damage equals to 0 indicates fully health condition and damage equals to 1.0 indicates collapse of the building. The vulnerability function was estimated using only one accelerometer located in three different points on the building. We recorded three acceleration records (ambient vibration), but these records were in three different intervals of time. This is a big limitation that can be covered by the SAVER platform, because the acceleration records must be at the same interval of time. The CWSN model can represent this easily, since it defines the evolution of the network, which can be represented through a succession of graphs.

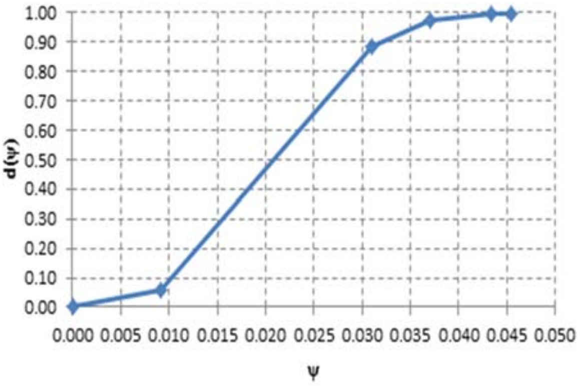


Fig. 6. Typical vulnerability function to establish the structural health condition on Building B.

The modeling and representation of the deployed WSN using the CWSN model can bring several advantages from the user and network manager's points of view. The main contribution of the CWSN model is to standardize ways to model a WSN and provide a unified view of such a network regardless of what aspects are considered. Moreover, it allows the user and the network manager to become more aware of the composition and state of the whole network. That is, the CWSN model allows for visually representing several details about the WSN that has been deployed, what provides them with a more intuitive and prompt understanding of the WSN.

5. Conclusions

The CWSN model also defines the evolution of the network, which can be represented through a succession of graphs.

In this extended version of the paper [29], we presented the CWSN model, which is based on the CSCW methodology and specifically designed for WSNs. The great advantage of using this model to represent WSNs is that, besides modeling collaboration, it can also model the entire WSN. Also, this model allows for the representation of each state of the network and its evolution. Moreover, the CWSN model is generic, in the sense that it can be applied to heterogeneous WSNs, and scalable, as it can be updated if any modifications need to be introduced. The CWSN model was formalized in first-order logic. This attribution allows knowing which edges are active and which are not. In other words, we are able to identify which nodes are transmitting information. If some failure occurs on the process of transmission, our approach allows identifying this situation.

We consider that some advantages of the CWSN model arise from the fact of being formal and based on graphs.

The attributes defined for each entity of the CWSN model cover several dimensions. Thus, this model can be used as a framework for developing more generic software solutions for WSNs. Given the fact of being a broad and generic model, also confers the CWSN model with the ability of being applied to describe any WSN regardless of its application scenario.

We also believe that this model can assist network designers in making better decisions regarding the organization and management of the network. This contribution becomes more significant given that the CWSN model was used as a basis to implement an awareness tool and a sessions' managing tool for WSNs, which will be described in the next chapter.

Moreover, the CWSN model can be used to automatically generate some graphs of the WSN that will allow for identifying routing paths, detecting damaged/failed nodes or links, etc.

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