A Collaborative Model for Representing Wireless Sensor Networks' Entities and Properties

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ABSTRACT
Wireless sensor nodes are, typically, resource limited. Therefore, the major functions of the Wireless Sensor Network (WSN) cannot be accomplished without collaboration among sensor nodes. In this paper, we present the Wireless Sensor Networks Supported Cooperative Work (WSNSCW) model. The key contribution of this model, when comparing to other models, is allowing for the representation of all the components and properties of a WSN. We also present the main entities and properties of this graph-based model, as well as its formalization.

Categories and Subject Descriptors
I.6.5 [**Simulation and Modeling**]: Model Development – *modelling methodologies*.

General Terms: Theory, Standardization.

Keywords: Wireless Sensor Networks, Collaboration, CSCW, Graph-based Model.

1. INTRODUCTION
In general, a Wireless Sensor Network (WSN) consists of a large number of tiny wireless sensor nodes that are, typically, densely deployed [1]. These nodes measure some phenomenon in the environment surrounding them. Then, these measurements are sent to the user via a sink node (or Base Station), in a multi-hop basis.

On one hand, due to wireless communications, WSNs allow for a wide range of applications: environmental monitoring, catastrophe monitoring, health, surveillance, traffic monitoring, security, military, industry, agriculture, etc. On the other hand, wireless sensor nodes are intended to be small and cheap. Consequently, these nodes are typically resource limited (limited battery, reduced memory and processing capabilities) [1]. Moreover, due to short transmission range (caused by restrained transmission power), nodes can only communicate locally, with a certain number of local neighbours. Consequently, wireless sensor nodes have to collaborate in order to accomplish their tasks: sensing, signal processing, computing, routing, localization, security, etc. Thus, WSNs are, by nature, collaborative networks. Collaboration enhances the scalability of the network and facilitates mission completion [2].

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According to [3], WSNs originated a new collaboration concept. In traditional networks, collaboration exists within the same group of nodes, even though they move (node-centric collaboration). In WSNs, collaboration usually occurs among nodes located in a certain region, which means that the group of nodes may not be the same (location-centric collaboration). However, besides localization-based collaboration, it is possible to identify other ways to collaborate, based whether in monitoring a certain phenomenon or in the hardware characteristics of the nodes themselves [4], [5], [6].

In this paper, we present a graph-based, generic and hierarchical model of cooperative work designed for the specific case of WSNs, named Wireless Sensor Networks Supported Cooperative Work (WSNSCW). It allows not only for the modelling of collaborative work (based in CSCW concepts), but also for the modelling of all the entities that can constitute a WSN, as well as its properties.

This paper is organized as follows. In section 2, we briefly describe the related work. In section 3, the WSNSCW model and its entities are defined and formalized. Section 4 provides some conclusions and perspectives of future work.

2. RELATED WORK
Even though there are several works concerning collaboration in WSNs, they only focus a specific type of collaboration, which is associated with the accomplishment of a certain task, such as: sensing [7], signal processing [3], computing [8], routing [9], localization [10], security [11], task scheduling [12], heuristics [13], calibration [14], resource allocation [15], time synchronization [16], transmission [17], etc. There are also works concerning collaboration between wireless sensor nodes and other kind of devices (heterogeneous groupware collaboration) to support some specific applications (for e.g., collaboration between sensor nodes and PDAs, in a fire fighting scenario) [18], [19].

The only work found in literature that presents a model for collaborative work in sensor networks, to date, has been proposed by Liu et al. [20]. It is the SNSCW (Sensor Networks Supported Cooperative Work) model. It is a hierarchical model that divides cooperation in sensor networks in two layers. The first one relates to cooperation between humans and sensor nodes (user-executor relationship, being initiated either by the user or by the sensor node), and the other layer relates to cooperation between the sensor nodes (considers two main subtypes of cooperation: peer-to-peer and master-to-slave).

This model was designed for sensor networks. However, it does not consider the specific requirements of WSNs, for instance, its scale, its self-configuration and self-maintenance requirements, the resource limitations of wireless sensor nodes, etc. Also, it only allows for modelling of collaboration itself.

3. WSNSCW MODEL

In this section, we present the Wireless Sensor Networks Supported Cooperative Work (WSNSCW) model. As WSNSCW is a model of collaborative work created specifically to WSNs, it considers the particular requirements of WSNs. It is, essentially, a graph-based model; nevertheless, it includes other objects in order to make the modelling of all the entities of a WSN possible. This is fundamental to completely represent a WSN.

3.1 WSNSCW Model Definitions

In this section, the entities of our model are described. 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 (usually, the more powerful node), 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 (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.

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 goals.

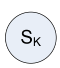
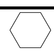
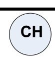
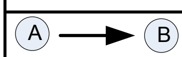
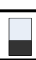
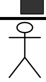
As *battery* is the most critical resource of a sensor node, it is really important that the user knows the state of the battery of each sensor. That is why the battery is also an entity of our model.

Finally, 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.

3.2 WSNSCW Model Formalization

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

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

Symbol	Concept	Description
	Sensor node	Wireless sensor nodes, typically with limited resources. These nodes can be either stationary or mobile. Also, they can be in one of two possible states: active or inactive (sleep mode) in order to save energy.
	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 (see section 3.2); nodes A and B are neighbours. 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 obstructs line-of-sight between two or more nodes, not allowing for direct communication between them.
	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.

3.2.1 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.

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 producer-consumer relationship. Considering, for example, two nodes: A and B; the arrow (A) ⟶ (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.

Assuming Nr is the total number of sensor nodes that constitute the WSN, let $\mathcal{N} = \{1, 2, \ldots, Nr\}$. Let's represent a wireless sensor node by N_i, with $i \in \mathcal{N}$.

The WSN has a limited lifetime, which can vary from some hours to several months or years. Denoting by LT the lifetime of the network (in seconds), let $\mathcal{T} = \{1, 2, \ldots, LT\}$ and t_j represent the j^{th} second of life of the network, with $j \in \mathcal{T}$.

3.2.2 Sensor Node (Ni)

A sensor node (N_i) is defined by:

$N_i = \{ I_D, TS, CM, R, Ty, S, B, L, TM\}$

Table 2 defines and formalizes the properties that are important to identify a sensor node (N_i).

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

	Properties	Description / Formalization
Sensor Node (N_i)	Identifier (I_D)	Each sensor node has a unique identifier (I_D) $I_D (N_i) = i$, $i \in \mathbb{N}$
	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), etc. So, TS (N_i) $\subseteq$ {Li, Te, Hu, Sd, Iv, Ac, Pr, Vb, ...}
	Communication modality (CM)	A number of communication modalities can be used, such as: radio (RF), light (Li), ultrasound (US), acoustical (Ac), hybrid (Hy). So, CM (N_i) $\subseteq$ {RF, Li, US, Ac, Hy}
	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 [17]: $R = P_t/P_{th}$ 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, $\varepsilon>0$ [17].
	Type (Ty)	Alphanumeric that identifies the brand and the model of the sensor node. Ty (N_i) = {Brand (N_i), Model (N_i)}
	State (S)	Depending on its power mode, the node N_i can be in one of two states (S): Active (Ac): Node which is in the active state. Inactive (In): Node which is in the sleep mode, in order to save energy. So, S (N_i) = Ac or S (N_i) = In
	Battery (B)	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 $T_B (N_i) \in$ {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: $P_{BNi} (t_j)$ [%] $B_{Ni} (t_j) = \{T_B (N_i), C_B (N_i), P_{BNi} (t_j)\}$
	Localization (L)	Let $L_{Ni} (t_j)$, with $i \in \mathcal{N}$ and $j \in \mathcal{T}$, 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 $x, y, z \in \mathbb{R}$ 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 $a, b, c \in \mathbb{R}$ are known.
	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: $\exists\, j, l \in \mathcal{T}: L_{Ni} (t_j) \neq L_{Ni} (t_l)$, and $j \neq l \;\wedge\; \exists\, r, s \in \mathcal{T}: L_{Ni} (r) = L_{Ni} (r+1) = \ldots = L_{Ni} (s)$, and $s >> r$ Continuous (Cont): $\forall\, j \in \mathcal{T} \setminus \{LT\}\; L_{Ni} (t_{j+1}) \neq L_{Ni} (t_j)$ 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 (N_i) $\in$ {St, {OcMb, Inc}, {OcMb, Des}, {ContMb, Inc}, {ContMb, Des}}

Table 3. Definition and formalization of some of the properties of the entity Sink Node (S_K).

S_K	Stationary (StS_K)		Mobile (MbS_K)	
Sink Node (S_K)	**Properties**	**Description/ Formalization**	**Properties**	**Description / Formalization**
	Localization (L)	Defined by L_{StSK}, the localization of a stationary sink node is well-known and independent of time.	Localization (L)	Defined by L_{MbSK}, the localization of a mobile sink node varies as it moves along the network.
	Type of Mobility (TM)	TM (StS_K) = St	Type of Mobility (TM)	• Continuous: TM (MbS_K) = {ContMb, Des} • When necessary (the sink node can move in order to allow for other sensor nodes to communicate with it): TM (MbS_K) = {OcMb, Des}
	Power supply (PS)	▪ Battery (B) ▪ Solar cells (SC) ▪ External and unlimited power supply (VDC) ▪ Etc. PS (StS_K) $\subseteq$ {B, SC, VDC, etc.}	Power supply (PS)	▪ Battery (B) ▪ Solar cells (SC) PS (MbS_K) $\subseteq$ {B, SC}

Reachable property: two nodes are able to communicate if they are adjacent and if the distance (d) between them is less than their maximum transmission range (R):

$d(a,b) < R(a) \wedge d(a,b) < R(b) \Rightarrow$ a and b are reachable.

This property verifies:

Adj (a,b): bool
Adj (a,b) $\Rightarrow$ reachable (a,b)
$\exists$ c: reachable (a,c)
Adj (c,b) $\Rightarrow$ reachable (a,b)

3.2.3 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 node 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.Only the properties that distinguish the sink node from the ordinary sensor nodes are described and formalized in Table 3.

3.2.4 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, that will 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}.

3.2.5 Network (WSN)

In Table 4, we define and formalize all the properties that are important to define the entity network (WSN). So, a WSN is defined by:

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

3.2.6 Cluster (C)

If a clustering algorithm is applied, clusters will be formed [22]. 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. So, a cluster (C) is defined by:

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

Even though clustering is influenced by the network and link layer protocols, some attributes can be identified (presented in Table 5).

3.2.7 Cluster Head (CH)

A cluster head (CH) is may be elected by the sensors in a cluster or pre-assigned by the network designer. A CH may also be one of the nodes that is richer is resources. Moreover, the cluster membership may be fixed or variable. So, a cluster head (CH) is defined by [22]:

CH = {TM, TN, Ro}.

Table 4. Definition of the properties of the entity Network (WSN).

	Properties	Description / Formalization
Network (WSN)	Topology (To)	The WSN can have different topologies (To): Single-hop, Star, Networked stars, Tree, Graph and Grid. So, To $\in$ {Single-hop, Star, Net-Stars, Tree, Graph, Grid}
	Mobility (M)	There are some different possible scenarios, regarding mobility of sensor nodes: ▪ All nodes are stationary: $\forall$ i $\in \mathcal{N}$, $\forall$ j, l $\in \mathcal{T}$ $L_{Ni}(t_j) = L_{Ni}(t_l)$ ▪ All nodes are mobile: $\forall$ i $\in \mathcal{N}$, $\exists$ j, l $\in \mathcal{T}$: $L_{Ni}(t_j) \neq L_{Ni}(t_l)$, and $j \neq l$ ▪ Only some nodes move: $\exists$ i $\in \mathcal{N}$, $\exists$ j, l $\in \mathcal{T}$: $L_{Ni}(t_j) \neq L_{Ni}(t_l)$, and $j \neq l$ $\wedge$ $\exists$ p $\in \mathcal{N}$: $L_{Np}(t_1) = L_{Np}(t_2) = \ldots = L_{Np}(t_{LT})$
	Homogeneity (H)	A WSN can be: ▪ Homogeneous (Ho), when it is composed by homogeneous devices, which means that sensor nodes are mostly identical from a hardware and a software point of view. Ho: $\forall$ i, p $\in \mathcal{N}$, Md (N_i) = Md (N_p) and $i \neq p$ ▪ Heterogeneous (He), when it is composed by heterogeneous devices, which means that sensor nodes are mostly different from a hardware and a software point of view, for e.g., in type and number of attached sensors (TS). He: $\exists$ i, p $\in$ N : Md (Ni) $\neq$ Md (Np) So, H = Ho or H= He
	Number (Nr)	Total number of sensor nodes (N_i) that constitute the WSN, which may vary from a few nodes to thousands of sensor nodes. Nr $\in \mathbb{N}$
	Area (A)	Area of deployment (m^2). A $\in \mathbb{R}^+$
	Coverage (C)	A WSN can have different types of coverage: ▪ Sparse (Sp), when the network coverage is much smaller than its deployment area. ▪ Dense (De), when the network coverage coincides with its deployment area, or comes close to it. ▪ Redundant (Re), when multiple sensors cover the same area. So, C $\in$ {Sp, De, Re}
	Density (D)	Network density can be defined in terms of number of nodes per nominal coverage area [21]: $D = (Nr \times \pi \times R^2) / C_A$, where C_A is the area that is covered by the whole network. C_A (m^2) $\in \mathbb{R}^+$ Note that the coverage area (C_A) may be different from the deployment area (A).
	Hierarchy (Hi)	Clusters may be created according to: geographical area, type of sensor nodes, type of phenomenon to monitor, etc., providing the WSN with a hierarchical structure. All clusters must have a cluster head (CH).
	Number of sink nodes (NS_K)	A WSN has one or more sink nodes. A sink node can be stationary (StS_K) or mobile (MbS_K). NS_K < Nr
	Number of anchor nodes (NA)	Anchor nodes are nodes with known location. They can be stationary or mobile: ▪ Stationary anchor node (StA) ▪ Mobile anchor node (MbA) NA < Nr
	Number of Clusters (NC)	The number of clusters (NC) can be: ▪ Preset (Pr): In some approaches, the set of CHs are predetermined and thus the number of clusters (NC) is preset. ▪ Variable (Var): Randomly picking CHs from the deployed sensor nodes usually leads to a variable number of clusters. So, NC = Pr or NC = Var
	Number of Obstacles (NO)	NO $\in \mathbb{N}$
	Lifetime (LT)	Deployment may be: ▪ One-time activity. In this case, LT = K with K $\in \mathbb{N}$ ▪ Iterative (continuous) process. In this case, LT $\approx \infty$

3.2.9 Session (Se_i)

A session is the essential unit of a collaborative activity, which can be established based on different objectives. 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 subgraph, *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. Table 7 presents the properties that are unique to the entity session.

Similarly to a sensor node (N_i), a session (Sei) can be in one of two states: Active (Ac), or Inactive (In), when its objective is fulfilled. So, S (Se_i) = Ac or S (Se_i) = 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.

Table 5. Definition and formalization of some of the properties of the entity Cluster (C_i).

	Properties	Description / Formalization
Cluster (C_i)	Stability (Stb)	Regarding stalability (Stb), the membership of sensor nodes can be: ▪ Fixed (Fix): Sensor nodes do not switch among clusters and the number of clusters stays the same throughout the network lifetime. ▪ Adaptive (Adp): The number of clusters varies and the membership of the sensor nodes changes overtime. Stb (C) ∈ {Fix, Adp}
	Number of Sensor Nodes (NrC)	Depending on the type of clustering algorithm implemented and accordingly to the Stability property, the number of sensor nodes per cluster (NrC), may be fixed (Fix) or variable (Var). So, NrC=Fx or NrC=Var
	Intra-cluster Topology (IaC-To)	Inside a cluster, connectivity may be: ▪ Direct link (D-L): Based on direct communication between a sensor node and its designated CH. ▪ Multi-hop (M-H): When the sensor node's transmission range is limited and/or the CHs are preset, a multi-hop connection from the sensor node to the CH may be required. So, IaC-To (C) ∈ {D-L, M-H}
	Inter-CH Connectivity (IeCH-Con)	Connectivity between the CHs and the sink node must be guaranteed. When the CHs do not have a long transmission range, the clustering scheme has to ensure the feasibility of establishing an inter-CH route from every CH to the sink node.
	Clustering Methodology (CMet)	The clustering methodology may be: ▪ Distributed: Clustering has to be performed in a distributed manner, without coordination, when CHs are just regular sensor nodes. ▪ Centralized: A centralized authority coordinates the entire clustering process; it controls de cluster membership. ▪ Hybrid: these schemes are more usual when CHs are nodes richer in resources; typically, inter-CHs coordination is performed in a distributed manner, while each individual CH is in charge of forming its own cluster. So, CMet ∈ {Dist, Cent, Hyb}

Table 6. Definition and formalization of some of the properties of the entity Cluster Head (CH).

CH	Properties	Description / Formalization
Cluster Head (CH)	Type of Mobility (TM)	Regarding mobility, a cluster head (CH) may be: ▪Stationary CHs (StCHs): tends to yield stable clusters and facilitate intra-cluster and inter-cluster network management. ▪Mobile CHs (MbCHs): sensor nodes' membership dynamically changes and the clusters need to be continuously maintained. ▪Re-locatable CHs (ReCHs): Sometimes, CHs can move for limited distances to reposition themselves for better network performance. So, TM (CH) ∈ {StCHs, MbCHs, ReCHs}
	Types of Nodes (TN)	Depending on the setup: ▪Sensor node: A subset of the deployed sensor nodes are designated as CHs or ▪Resource-rich: CHs are equipped with significantly more computation and communication resources.
	Role (Ro)	A CH can act as a relay for the traffic generated by the sensor nodes that belong to its cluster (Relay), perform aggregation/fusion of sensor's collected data (Agreg) or, sometimes, it can take actions based on the detected phenomenon or targets (acts as a sink node) (S_K). So, Ro (CH) ∈ {Relay, Agreg, S_K}

So, a session (Se_i) is defined by the following properties:

Se_i = {I_D, SeObj, SeT_{Life}, To, S, Nr, NS_K, NA, NC, NO, DTx}.

Note that topology (To) has the same definition than 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) and NO (Se_i) ≤ NO (WSN).

3.3 Example Scenario

In this section, we validate the WSNSCW model by applying it to the specific case of an environmental monitoring application. This work was developed in the context of an European project, named FORESMAC (Project INTERREG III B, 05/MAC/2.3/C16). The purpose of this project is to create a WSN in order to accomplish environmental monitoring of forests.

Table 7. Definition and formalization of some of the properties of the entity Session (Se).

	Properties	Description / Formalization
Session (Se)	Objective (Obj)	A session is the essential unit of a collaborative activity, which can be established based on different objectives: type of phenomenon to monitor (phen_mon), geographical area to monitor (area_mon), monitoring period (per_mon), etc. So, Obj (Se_i) $\subseteq$ {phen_mon, area_mon, per_mon, etc.}.
	Data Transmission Model (DTx)	Depending on the application, the data transmission model can vary. Consequently, a session can be: ▪Continuous (Cont): sensor nodes transmit continuously at a predetermined rate ▪Event-oriented (E-O): sensor nodes only transmit data if an event occurs ▪User initiated (U-I): sensor nodes only send data if the user explicitly requests it ▪Hybrid (Hyb): where these three types co-exist So, DTx (Se_i) $\subseteq$ {Cont, E-O, U-I, Hyb}
	Lifetime of the session (SeT_{Life})	Let SeTLife be the period of time during which a session is active. It is important that the user knows the exact instant when the session started (SeTstart) and when it ended, becoming inactive (SeTend). So, SeTLife = { SeTstart, SeTend}

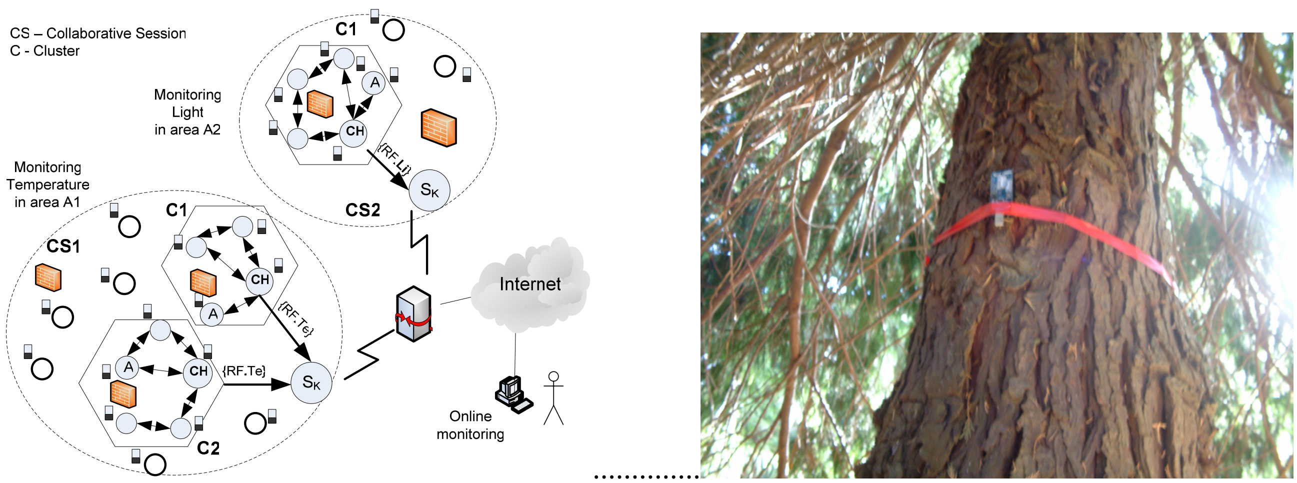


Figure 1. Applying the WSNSCW model to a forest environmental monitoring application.

So, let's consider the example of a forest monitoring WSN. As Figure 1 illustrates, there are 2 simultaneous collaborative sessions. These sessions where initiated by the user, with two different objectives: to monitor the temperature of area A1 (CS1) and to monitor the light of area A2 (CS2). Nodes were deployed, in an ad hoc manner, in two different geographical areas of a forest. There are 2 sink nodes, 3 anchor nodes and 16 wireless sensor nodes. Within each area, clusters have been created; there are 2 clusters in Area A1 and 1 cluster in area A2; hence, there are 3 cluster heads (CH).

As this scenario relates to an environmental monitoring application, it is very important to be able to correlate collected data in space. So, anchor nodes had to be deployed. The nodes that belong to a cluster are in the active state, whereas the remaining nodes are in the sleep mode. The user is typically far away from the forest being monitored. So, he monitors the WSN through the Internet.

Any changes that might occur on this scenario (new collaborative sessions, new clusters, nodes changing from sleep mode to the active state or vice versa, nodes moving, etc.) can be represented by a sequence of figures analogous to Figure 1.

By using the WSNSCW model to represent the WSN, gives the user a better understanding of the network operation, through the an easy identification of the different components of the network (different types of nodes; different states of the nodes; battery of the nodes, since it is the most critical resource; the existence of clusters; sink nodes; sessions; types of collected data; types of transmitted signals; etc.), their properties, their relationships, their states, etc.

3.4 Advantages of the WSNSCW Model

Opposing to the SNSCW model [20], our model not only allows for modelling of cooperation within the network, but also for modelling of the entire WSN. This model also allows for the representation of the network hierarchy, from the collected data to the user (passing through the clusters, the session and the WSN), and for the representation of each state of the network and its evolution. Moreover, WSNSCW is a generic model, in the sense that it can model heterogeneous networks. 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 of its specific application. So, it is possible to use all the entities defined in the model to represent a certain scenario of any specific application (monitoring a forest, a vineyard, a volcano, a museum, a natural catastrophe, etc.). Any changes that might occur on this scenario (new collaborative sessions, new clusters, nodes moving, etc.) can be represented by a sequence of figures.

Regarding collaboration, the model includes some fundamental CSCW (Computer Supported Cooperative Work) concepts (such as: session, relationship, data flow and groups) and properties (such as: producer-consumer and flow control).

4. CONCLUSIONS AND FUTURE WORK

In this paper we presented the WSNSCW model, a model that is based in the CSCW methodology and specifically designed for WSNs. The great advantage of this graph-based model lies in the fact that, besides modelling collaboration, it also allows for the modelling of the entire WSN. Also, this model allows for the representation of each state of the network and its evolution.

In this paper, we applied the model to an environmental monitoring application. However, this is a generic model that can be applied to a heterogeneous WSN, in the sense that it can be applied to any type of sensors and any type of application.

The WSNSCW model is being used for the development of a 3D awareness tool that will allow for an interactive navigation in the map of the network. The 3D representation of the network is very important for an awareness tool, so the user can have a more realistic view of the network. This tool will allow for the visualization of all the components of a WSN, its properties, its hierarchy and, also, for the visualization of different granularities.

Regarding collaboration, we intend to include more CSCW concepts and properties.

5. REFERENCES

[1] Akyildiz, I., Su, W., Sankarasubramaniam, Y., Cayirci, E., "A Survey on Sensor Networks", *IEEE Communications Magazine*, Aug. 2002, 102-109.

[2] Römer, K., Mattern, F., "The Design Space of Wireless Sensor Networks", IEEE Wireless Communications, Vol. 11, No. 6, Dec. 2004, 54-61.

[3] Ramanathan, P., Saluja, k., Hu, Y., "Collaborative Sensor Signal Processing for Target Detection, Localization and Tracking", in Proc. of 23rd Army Science Conference, Dec. 2002.

[4] Gracanin, D., Adams, K., Eltoweissy, M., "Data Replication in Collaborative Sensor Network Systems", in Proc. 25th IEEE International Performance, Computing, and Communications Conference (IPCCC 2006), 10-12 April 2006, 389-396.

[5] Ranjan, G., Kumar, A., Rammurthy, G., Srinivas, M., "A Natural Disasters Management System Based on Location Aware Distributed Sensor Networks", IEEE International Conference on Mobile Ad hoc and Sensor Systems (MASS 2005), 2005.

[6] Medidi, M., Slaaen, R., Zhou, Y., Mallery, C., Medidi, S., "Cluster-based Localization in Wireless Sensor Networks", in Proc. of the SPIE, Wireless Sensing and Processing, Raghuveer M. Rao, Sohail A. Dianat, Michael D. Zoltowski., Editors, Volume 6248, 62480J, May 2006.

[7] Wang, K.-C., Ramanathan, P., "Collaborative Sensing Using Sensors of Uncoordinated Mobility", International Conference on Distributed Computing in Sensor Systems (LNCS), Marina del Rey, USA, June 2005, 293-306.

[8] Iftode, L., Borcea, C., Kang, P., Cooperative Computing in Sensor Networks, Handbook of Sensor Networks: Compact Wireless and Wired Sensing Systems, Mohammad Ilyas (ed.), CRC Press, July 2004.

[9] Chen, G., Guo, T.-D., Yang, W.-G., Zhao, T., "An improved ant-based routing protocol in Wireless Sensor Networks", International Conference on Collaborative Computing: Networking, Applications and Worksharing (CollaborateCom 2006), Nov. 2006, 1-7.

[10] Dardari, D., Conti, A., "A Sub-Optimal Hierarchical Maximum Likelihood Algorithm for Collaborative Localization in Ad-Hoc Networks", 1st Annual IEEE Communications Society Conference on Sensor and Ad Hoc Communications and Networks (IEEE SECON 2004), Oct. 2004, 425- 429.

[11] Chadha, A., Liu, Y., Das, S., "Group Key Distribution via Local Collaboration in Wireless Sensor Networks", 2nd Annual IEEE Communications Society Conference on Sensor and Ad Hoc Communications and Networks (SECON 2005), Santa Clara, California, USA, Sept. 2005.

[12] Sanli, H., Poornachandran, R., Cam, H., "Collaborative Two-Level Task Scheduling for Wireless Sensor Nodes", in Proc. of IEEE Communications Society Conference on Sensor and Ad Hoc Communications and Networks (SECON 2005), Santa Clara, USA, Sep. 2005.

[13] Reghelin, R., Fröhlich, A., "A Decentralized Location System for Sensor Networks Using Cooperative Calibration and Heuristics", in Proc. of 9th ACM international symposium on Modeling Analysis and Simulation of Wireless and Mobile Systems (MSWiM'06), Torremolinos, Spain, 2006, 139-146.

[14] Bychkovskiy, V., Megerian, S., Estrin, D., Potkonjak, M., "A Collaborative Approach to In-Place Sensor Calibration", 2nd International Workshop on Information Processing in Sensor Networks (IPSN'03), April 2003.

[15] Giannecchini, S., Caccamo, M., Shih, C.-S., "Collaborative resource allocation in wireless sensor networks", in Proc. of Euromicro Conference on Real-Time Systems (ECRTS'04), June/July 2004, 35–44.

[16] Hu, A., Servetto, S., "Algorithmic Aspects of the Time Synchronization Problem in Large-Scale Sensor Networks", Mobile Networks and Applications, 10, 2005 Springer Science + Business Media Inc., 2005, 491-503.

[17] Krohn, A., Beigl, M., Decker, C., Riedel, T., Zimmer, T., Varona, D., "Increasing Connectivity in Wireless Sensor Network using Cooperative Transmission", 3rd International Conference on Networked Sensing Systems (INSS), Chicago, USA, May 31 – June 2, 2006.

[18] Cheng, L., Lian, T., Zhang, Y., Ye, Q., "Monitoring Wireless Sensor Networks by Heterogeneous Collaborative Groupware", Sensors for Industry Conference (Sicon/04), New Orleans, Louisiana, USA, 27-29 Jan. 2004.

[19] Chaczko, Z., Ahmad, F., Mahadevan, V., "Wireless Sensors in Network Based Collaborative Environments", 6th International Conference on Information Technology Based Higher Education and Training (ITHET 2005), July 2005, F3A-7-F3A-13.

[20] Liu, L., Ma, H., Tao, D., Zhang, D., "A Hierarchical Cooperation Model for Sensor Networks Supported Cooperative Work", in Proc. of 10th International Conference on Computer Supported Cooperative Work in Design (CSCWD'06), May 2006, 1-6.

[21] Bulusu, N., Estrin, D., Girod, L., Heidemann, J., "Scalable Coordination for Wireless Sensor Networks: Self-Configuring Localization Systems", Proc. of the 6th International Symposium on Communication Theory and Applications (ISCTA'01), Ambleside, UK, July 2001, 1-6.

[22] Abbasi, A., Younis, M., "A survey on clustering algorithms for wireless sensor networks", Computer Communications, vol. 30, no. 14-15, October 2007, 2826–2841.