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Dynamic Energy-Aware Sensor Configuration in Multi-Application Monitoring Systems

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Abstract

A typical pervasive monitoring system like a smart building depends on an infrastructure composed of hundreds of heterogeneous wireless sensor devices. Managing the energy consumption of these devices poses a challenging problem that affects the overall efficiency and usability. Existing approaches for sensor energy consumption typically assume a single monitoring application to consume sensor data and a static configuration for sensor devices. In this paper, we focus on a multi-application context with dynamic requirements and multi-modal sensor devices. We present 3SoSM, an approach to optimize interactions between application requirements and wireless sensor environment in real-time. It relies on an energy-aware dynamic configuration of sensor devices to lower energy consumption while fulfilling application requirements. To bind together sensor configuration and dynamic management of data streams, we design a sustainable multi-application monitoring system architecture for pervasive environments that collects application requirements for sensor data streams and optimizes them into sensor configurations. To demonstrate the effectiveness of our approach, a set of experiments are designed in the context of smart buildings. We comparatively evaluate our approach to show how dynamic sensor configuration for multiple monitoring applications indeed outperforms the mainstream duty-cycling method.

Keywords: pervasive environment, sensor data management, continuous query processing, wireless sensor network

1 **1. Introduction**

2 Smart building applications have long gained attention in the scientific
3 community and nowadays in the industry. Buildings, whether smart or not,
4 are among the primary consumers of the available energy sources today.
5 Therefore, considerable effort is poured into the design of smart buildings
6 where energy consumption is tried to get decreased without sacrificing the
7 satisfaction of the occupants. To accomplish this aim, the components of
8 the building itself, as well as the context of its users, should be continuously
9 monitored by means of streams of data from sensory inputs.

10 A typical pervasive monitoring system like a smart building consists of
11 multi-modal wireless sensor devices that are equipped with sensing, pro-
12 cessing and communication facilities. Sensing part can measure physical
13 quantities about the environment with some given sampling rate (sampling
14 frequency), processing part is able to do some computation on the measured
15 values and communication part is able to listen and send data packets to
16 other sensor devices. These deployed wireless devices are autonomous in
17 terms of energy: they have limited energy and battery lifetime. Smart build-
18 ing technology mainly relies on such wireless sensing infrastructure. In this
19 field, initial commercial solutions are **Building Automation Systems** where
20 a specific set of functionalities such as heating and ventilation control and
21 lighting management is implemented by a single vendor. However, as the sen-
22 sor infrastructure is becoming a standard component incorporated into the
23 design and construction of the modern buildings, flexible application devel-
24 opment by a third party is becoming an issue rather than the infrastructure
25 itself.

26 In this context, one of the main contributions of this paper is to allow
27 multiple applications to exploit the same smart building infrastructure while
28 considering energy consumption of the sensor devices in this infrastructure.
29 Our energy-aware monitoring system continuously adapt to various appli-
30 cation requirements, to building actual context and to user configuration.
31 These applications operate on a network of multi-modal wireless sensor de-
32 vices and use declarative continuous queries to exploit sensor data streams.
33 Application requirements as declared by the application developer can be
34 fulfilled in a multitude of ways: our method translates these requirements as
35 energy efficient acquisition and transmission schedules for the wireless sensor

36 network. We propose *Smart-Service Stream-oriented Sensor Management*
37 (**3SoSM**), an approach to optimize interactions between application require-
38 ments and the wireless sensor environment in real-time. The core of our ap-
39 proach is the definition of a Schedule Time Pattern with acquisition, trans-
40 mission and reception actions for each device configuration. The dynamic
41 reconfiguration of devices is performed through the real-time update and op-
42 timization of Schedule Time Patterns according to application requirements
43 that may change over time. With this approach, we expect to avoid unnec-
44 essary data measurements that may occur with static configuration and to
45 promote grouped or even compressed data transmission when possible.

46 In this article, Section 2 presents an overview of our multi-application
47 monitoring system architecture. Formalization of our approach is explained
48 in Section 3 and the energy-aware optimization process is detailed in Sec-
49 tion 4. Section 5 gives a brief description of our experimental platform to
50 implement our approach and Section 6 describes the experiments we con-
51 ducted. Experiment results are discussed in Section 7. Related works are
52 given in Section 8 and finally, conclusions are given in Section 9.

53 **2. Overview of 3SoSM**

54 Our **3SoSM** approach focuses on a multi-application monitoring system
55 with multi-modal sensor devices (i.e. devices that can measure different phys-
56 ical quantities) and provides finer sensor configuration than duty-cycle and
57 similar techniques. Our proposition of dynamic sensor management based
58 on real-time application requirements is performed at the gateway level, in
59 order to optimize energy consumption of sensor devices independently from
60 the application layer and/or the query engine.

61 *2.1. Monitoring Architecture for Smart Building Applications*

62 In this study, we adopt a “declarative monitoring architecture”, built
63 upon a **Pervasive Environment Management System (PEMS)** as presented
64 in [1, 2, 3]. Using declarative (*SQL-like*) continuous queries, an application
65 can easily interact with distributed devices like sensors. Figure 1 presents
66 our declarative monitoring application that has 4 main layers: Application,
67 PEMS Query Engine, PEMS Gateway and WSN (Wireless Sensor Network).
68 **Application** layer provides end-user access to the monitoring system. Ap-
69 plication requirements are defined at this layer and are declaratively ex-
70 pressed as a set of continuous queries over distributed services [1]. **PEMS**

71 **Query Engine** is responsible for managing query executions of queries com-
 72 ing from the Application layer. This layer integrates sensor devices as non-
 73 conventional, dynamic and heterogeneous data sources. To manage that, it
 74 includes a continuous query engine that interacts with services provided by
 75 the environment, in particular sensor services. **PEMS Gateway** stands for man-
 76 aging bidirectional communication and interactions between PEMS Query
 77 Engine and WSN. **WSN** layer represents wireless sensor devices that acquire
 78 physical quantity measures and can communicate with other sensor devices
 79 and physical gateways.

80 We use the **Service-Oriented Continuous**

81 **Query (SoCQ)** framework [1] for the PEMS
 82 **Query Engine**. The SoCQ engine handles
 83 a multi-application mechanism and sup-
 84 ports multiple parameterized stream sub-
 85 scriptions to the same device. Moreover,
 86 it supports real-time user configuration of
 87 applications and context-aware applications
 88 through queries that can dynamically com-
 89 bine data, streams and services. The user
 90 may insert complex continuous queries with conditions over data streams
 91 to trigger new interactions with services during their execution. Interac-
 92 tions with services (discovery, invocations of methods, subscriptions to data
 93 streams) are handled by **PEMS Gateway**. However, the SoCQ Engine itself
 94 does not overcome the reconfiguration of sensor devices, and thus assumes
 95 a pre-existing static configuration. Like for other approaches presented in
 96 the Related Works section, it is an issue for the energy enhancement of the
 97 system.

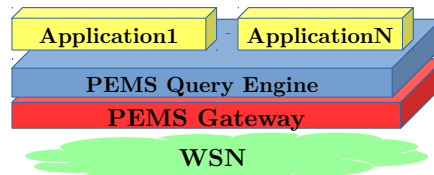


Figure 1: Declarative Monitoring Architecture.

98 *2.2. From Dynamic Application Requirements to Dynamic Sensor Configu-*
 99 *rations*

100 We consider that applications define their requirements as a set of con-
 101 tinuous queries over parameterized data streams produced by sensor devices.
 102 For instance: “*Application A1 computes the average temperature over the last*
 103 *10 minutes, with an update every 5 minutes, with an accuracy of 1 second and*
 104 *a maximum latency of 1 minute*”. In this example, the application requests
 105 temperature measure data streams from all devices with temperature sensors.
 106 To express the application requirements concerning sensor data management,
 107 we consider the following parameters targeting sensor measures: • **temporal**

108 **window** introduces the time interval for calculating the result (for the given
 109 example: 10 min); • **update periodicity** stands for the refreshing rate of
 110 the result (5 min); • **acquisition periodicity** represents the temporal
 111 accuracy of measures (1 sec); • **maximum latency** presents the maximum
 112 acceptable delay between the acquisition of data and its transmission to the
 113 PEMS layer for result calculation (1 min). **temporal window** and **update**
 114 **periodicity** concern the computing of the result, whereas **acquisition**
 115 **periodicity** and **maximum latency** are related to acquisition/transmission
 116 of data by sensor devices.

117 Here, we propose a novel approach: management and optimization of the
 118 real-time application requirements to enhance the energy consumption of the
 119 whole system. To fulfill the application requirements, we define a Schedule
 120 Time Pattern for each sensor device and configure devices accordingly. Our
 121 approach assumes that sensor devices are dynamically configurable [4].

122 3. 3SoSM Formalization

123 We consider that application requirements are parameterized stream sub-
 124 scription requests and the network topology is a tree topology. A solution
 125 to our optimization problem is individual Schedule Time Patterns, namely
 126 SCO-PATTERNS.

127 3.1. Application Requirements

128 Let D be the set of wireless sensor devices in the WSN environment. Each
 129 sensor device $d_i \in D$ may have multiple modalities to acquire different phys-
 130 ical quantity measures $m_i \in M$, e.g., temperature, humidity. Application
 131 requirements are defined in terms of data source requirements: targeted sen-
 132 sors d and requested measures m ; and of temporal requirements: temporal
 133 window β , update periodicity p^{upd} , acquisition periodicity p^{acq} and maximum
 134 latency λ . The unit is the second (or millisecond, if required).

135 For clarity, we do not present β, p^{upd} in this paper. We then represent
 136 application requirements on sensors at a given time instant by a set of pa-
 137 rameterized subscription requests $S = \{s_1, s_2, \dots, s_n\}$, where:

$$138 s_i = (d_i, m_i, p_i^{acq}, \lambda_i) \in D \times M \times \mathbb{N}^+ \times \mathbb{N}^+$$

139 **Example 1.** Suppose two applications with the following requirements on 6
 140 sensors:

141 **Application 1:** Temperature (m_T) of sensors d_1, d_3, d_5 with an acquisition

142 *periodicity of 2 sec and a latency of 4 sec;*

143 **Application 2:** *Humidity (m_H) of sensors d_3, d_4, d_5, d_6 with an acquisi-*
144 *tion periodicity of 5 sec and a latency of 3 sec.*

145 *Based on the previous notation, all application requirements are represented*
146 *by a set of parameterized subscription requests:*

$$147 S = \{(d_1, m_T, 2, 4), (d_3, m_T, 2, 4), (d_5, m_T, 2, 4), (d_3, m_H, 5, 3), (d_4, m_H, 5, 3),$$

148 $(d_5, m_H, 5, 3), (d_6, m_H, 5, 3)\}$

149 3.2. Network Topology

150 To transmit data to the central base station (where results are com-
151 puted), we suppose that deployed wireless sensor devices construct a logical
152 tree (tree topology) where each sensor has only one neighbor to deliver data
153 packets. This tree structure provides a uni-path for each sensor to reach
154 the base station (sink device). In fact, our optimization algorithm relies on
155 known and unique paths, as it does not consider a choice of network paths
156 between two devices. Integrating more complex network topologies, such as
157 mesh networks, would be a future work. However, the tree topology may be
158 updated each time application requirements change, as it triggers a new op-
159 timization. For instance [5] proposes a new technique to organize the sensor
160 devices that is likely preferable for outdoor monitoring systems: P-SEP (a
161 prolong stable election routing algorithm). The authors consider two-level
162 sensor device heterogeneities: advanced and normal devices. They propose
163 a clustering mechanism and present new cluster head selecting policy to ex-
164 tend the lifetime of the system (lifetime of the system is evaluated in terms
165 of FND (First Node Dies)). P-SEP puts forth efficient simulation results and
166 network lifetime. Although we do not tackle routing issues, applying our
167 dynamic network behavior due to the dynamicity of the application require-
168 ments, with the P-SEP mechanism could produce concrete improvements
169 on the lifetime of the system. In our case, with our assumptions about the
170 network, each sensor device has its own role in the topology based on the
171 current applications and its location: **Source** (responsible for the data ac-
172 quisition and transmission) and/or **Relay** (responsible for the reception and
173 re-transmission), or **Sink** (responsible for only the reception).

174 **Example 2.** *A tree topology with 6 multi-modal sensor devices and a base*
175 *station is illustrated in Figure 2. A tree topology has a layered form based on*
176 *the distance to the base station.*

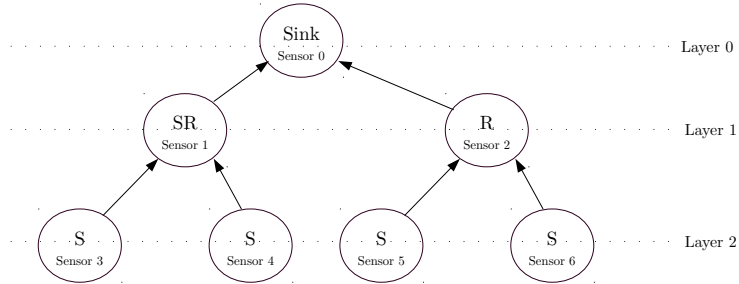


Figure 2: A tree-structured topology and different sensor device roles: Source (S), Relay (R), Source+Relay (SR), Sink.

177 **3.3. SCO-PATTERN**

178 The idea behind the 3SoSM approach is to create a **Schedule Time Pattern**
 179 for each sensor device. This pattern, described in [6] is a schedule composed of
 180 sensor actions, here with three types of actions: **acquisition A**, **reception**
 181 **R**, **transmission T**. Based on their roles, only certain actions are pertinent
 182 to sensor devices. Sensor devices can configure themselves with a Schedule
 183 Time Pattern, and then execute periodically the scheduled actions: acquire
 184 a measure and store it in a memory buffer, transmit all buffered measures
 185 one hop towards the sink (and empty the buffer), receive measures from a
 186 lower-layer device and store it in a memory buffer.

187 We call this pattern **sensor configuration oriented pattern** or SCO-
 188 PATTERN. This pattern consists of timestamped events ($\langle timestamp, action \rangle$)
 189 couples) and a length ℓ (or periodicity) of that pattern. These actions are
 190 enclosed by the length of the pattern: event timestamps are in time interval
 191 $[0; \ell[$. A SCO-PATTERN is denoted by:
 192 $P = (\{(t_i, a_i)\}, \ell)$ with $\ell \in \mathbb{N}^+$, $t_i \in [0; \ell[$, $a_i \in \{A_m, T, R\}$ where A_m indicates
 193 the data acquisition of the physical measure m such as A_T for temperature,
 194 A_H for humidity, etc.

195 **4. 3SoSM: Energy-Aware Optimization Process**

196 To optimize the energy consumption of the devices, since the communica-
 197 tion costs are the most significant part of the energy budget [7], we want to
 198 minimize the number of transmission and reception actions of each device:
 199 less communication means less consumed energy. We first construct “pre-
 200 liminary” SCO-PATTERNS that have a common length with only acquisition
 201 actions (Acq) for all the devices. It is then necessary to insert the trans-
 202 mission (Tx) and reception (Rx) actions in these SCO-PATTERNS to obtain
 203 a solution, composed of the set of complete SCO-PATTERNS. A solution is

204 valid if all acquired data traverse the network topology from their source
 205 device to the base station before the “latency” associated with that data
 206 expires. The optimal solution is a valid solution that minimizes the number
 207 of Transmission / Reception actions of each device.

208 The objective of the optimization process is to transform the applica-
 209 tion requirements into a global schedule and then to build individual SCO-
 210 PATTERNS to configure each device. Application requirements are represented
 211 by a set of subscription requests $S = \{s_1, s_2, s_3, \dots\}$. Hence the energy-aware
 212 optimization process can be expressed as a transformation function that gets
 213 a set of subscription requests (all subscription requests from all applications)
 214 and a network topology \mathcal{N} and produces a SCO-PATTERN for each device:
 215 $f(\{s_1, s_2, \dots, s_n\}, \mathcal{N}) = \{P_{d_1}, P_{d_2}, \dots, P_{d_m}\}$.

216 4.1. Preliminary SCO-PATTERN

217 The preliminary SCO-PATTERN is specific for each sensor device. It is pe-
 218 riodic, and its length indicates the periodicity. Each sensor device may have
 219 different acquisition periodicities from different applications. However, in or-
 220 der to build a global view of the network, a common length is required: it is
 221 the lowest common multiple of acquisition periodicities from all subscription
 222 requests. Moreover, the length of the schedule should be greater than any
 223 latency of the subscription requests to properly handle data expiration time:
 224 The final length is the lowest multiple of this initial common length greater
 225 than any data expiration time.

226 **Example 3.** *The common length of the patterns (for the given applications*
 227 *in Example 1) is calculated as:*

228 *Initial common length $\ell_{min} = LCM(2, 2, 2, 5, 5, 5, 5) = 10$*

229 *Maximum latency $\lambda_{max} = MAX(4, 4, 4, 3, 3, 3, 3) = 4$*

230 *Final length $\ell_{schedule} = 10 \text{ sec} > \lambda_{max}$*

231 Then, based on the periodicity of subscription requests, acquisition ac-
 232 tions are defined. Furthermore, each acquisition action is tagged with its
 233 maximum latency (from the subscription request).

234 **Example 4.** *Preliminary SCO-PATTERN for d_3 with subscriptions*

235 $\{(d_3, m_T, 2, 4), (d_3, m_H, 5, 3)\} :$

236 $P = (\{(0, \{A_T^4, A_H^3\}), (2, A_T^4), (4, A_T^4), (5, A_H^3), (6, A_T^4), (8, A_T^4)\}, 10)$

237 *4.2. Transmission Constraint and Optimization Goal*

238 To form a global schedule, we adopt a similar approach to Galpin et
239 al. [8]. A predefined granularity determines the slots in the time space: the
240 schedule is divided into time-slots and each slot may be filled with sensor
241 actions. For the following examples, granularity is set to 0.5 *sec* (e.g. 20
242 slots for 10 seconds).

243 The major constraint of the system is that all the acquired data must
244 pass through the network topology up to the base station before the expi-
245 ration of their “latency” in order to fulfill the application requirements. A
246 transmission action on a sensor device during a single time slot stands for a
247 transmission of all the data (acquired by itself and received from lower-layer
248 neighbors) not yet sent, including acquisitions on the same time slot. This
249 transmission action requires a reception action at the same time slot on the
250 sensor device that receives the data. Besides there are other constraints due
251 to the radio protocol such as a device can only receive data from a single
252 device at a time on the same time slot and a device can not receive and send
253 on the same time slot.

254 *4.3. Searching Optimal Communication Slots*

255 We propose an optimization algorithm to choose the optimal communi-
256 cation slots from the preliminary SCO-PATTERN. The optimization process
257 starts by propagating transmission and reception constraints due to the ac-
258 quisition events in a bottom-up process, and then analyzes the possible re-
259 ception actions of the base station and tries to find the most energy efficient
260 communication slots, and finally propagates those choices to lower layers and
261 continues the analyze in a top-down process.

262 *4.3.1. Schedule Table Initialization*

263 We use a schedule table to represent the sensor action slots for Tx/Rx.
264 Each sensor device has its own schedule and each schedule is composed of
265 two parts: transmission and reception part. The length of the schedule is
266 defined by the common length of preliminary SCO-PATTERNS. Each line
267 of the schedule table corresponds to an acquired measure: its transmission
268 action for the transmission part and its reception action for the reception
269 part.

270 The transmission part indicates the possible transmission slots for the
271 sensor device for each acquired measure. According to the latency informa-
272 tion λ , every sensor device has the initiative to keep the data (instead of

273 sending it immediately) and send it at an optimal later moment under the
 274 condition that this acquired data arrives at the base station before the ex-
 275 piration of its latency. The reception part represents the possible reception
 276 slots for each data coming from lower-layer neighbors (zero, one or several
 277 depending on the network topology). Schedule Table for Sensor 3, Sensor 1
 278 and Sensor 0 (sink device) are illustrated in Figure 3.

279 We propagate bottom-up constraints for data transmission and reception
 280 based on latencies (from preliminary SCO-PATTERNS) and on the network
 281 topology.

282 *Transmission Part.* Information from the preliminary SCO-PATTERN is used
 283 to fill the transmission part. For a given sensor device, each acquired data
 284 and each received data is represented as a line in the transmission part. A
 285 line is filled with the residual latency information starting from the time slot
 286 where the device acquires the data or from the time slot following the time
 287 slot where the device received the data, and until residual latency reaches 0
 288 (in fact, 1 time slot before at 1 hop from the sink, 2 time slots at 2 hops,
 289 etc.).

290 For each device d , $T_d = [e_{i,j}]$ is a 2D matrix with dimensions $m_d \times n$. m_d
 291 is the number of data to transmit and n stands for the number of time slots. $e_{i,j}$
 292 represents a potential transmission event of data i at time slot j : $e_{i,j} = \lambda_{i,j}$
 293 is the residual latency, $e_{i,j} = 0$ means that data i can not be transmitted at
 294 that time slot.

295 **Example 5.** *Transmission parts of the schedules of Sensors 3 and 1 are*
 296 *presented respectively in Figure 3a, 3b. For instance, Sensor 3 measures*
 297 *temperature and humidity values. For A2#1 (first acquisition for humidity),*
 298 *the latency is 3sec. Hence, to send that data, Sensor 3 has 5 slots ($t=0, 0.5, 1,$*
 299 *1.5, 2 sec) before the latency is expired as it is 2 hops from sink. Transmission*
 300 *part of the schedule of Sensor 1 covers transmission of its own data and also*
 301 *received data from Sensor 3 and 4 (see Fig 3b).*

302 *Reception Part.* For a given sensor device, the reception part is based on
 303 the transmission part of the schedules of lower-layer neighbors. Each line
 304 represents a data to receive and is linked to one line from the transmission
 305 part of the source device. Possible reception slots are filled with the data
 306 residual latency from the corresponding transmission time slot.

307 For each device d , $R_d = [e_{i,j}]$ is a 2D matrix with dimensions $m_d \times n$ where
 308 m_d is the number of data to receive and n stands for the number of time slots.

Acquisition	Measure	Time(sec)																				
		0	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6	6.5	7	7.5	8	8.5	9	9.5	
Acq of SA1	temperature	A1#1				A1#2				A1#3				A1#4				A1#5				
Acq of SA2	humidity	A2#1												A2#2								
Transmission	Id																					
TX of S3A1#1	S1																					
TX of S3A1#2	S1																					
TX of S3A1#3	S1																					
TX of S3A1#4	S1																					
TX of S3A1#5	S1																					
TX of S3A2#1	S1																					
TX of S3A2#2	S1																					

(a) Schedule of Sensor 3 (Acquisition + Transmission).

Acquisition	Measure	Time(sec)																				
		0	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6	6.5	7	7.5	8	8.5	9	9.5	
Acq of S1A1	temperature	A1#1				A1#2				A1#3				A1#4				A1#5				
Reception	From																					
RX of S3A1#1	S3																					
RX of S3A1#2	S3																					
RX of S3A1#3	S3																					
RX of S3A1#4	S3																					
RX of S3A1#5	S3																					
RX of S3A2#1	S3																					
RX of S3A2#2	S3																					
RX of S3A1#1	S4																					
RX of S3A1#2	S4																					
Transmission	Id																					
TX of S1A1#1	S0																					
TX of S1A1#2	S0																					
TX of S1A1#3	S0																					
TX of S1A1#4	S0																					
TX of S1A1#5	S0																					
TX of S1A1#1	S0																					
TX of S1A1#2	S0																					
TX of S1A1#3	S0																					
TX of S1A1#4	S0																					
TX of S1A1#5	S0																					
TX of S1A2#1	S0																					
TX of S1A2#2	S0																					
TX of S1A1#1	S0																					
TX of S1A1#2	S0																					

(b) Schedule of Sensor 1 (Acquisition + Reception + Transmission).

Reception	From	Time(sec)																			
		0	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6	6.5	7	7.5	8	8.5	9	9.5
RX of S1A1#1	S1																				
RX of S1A1#2	S1																				
RX of S1A1#3	S1																				
RX of S1A1#4	S1																				
RX of S1A1#5	S1																				
RX of S3A1#1	S1																				
RX of S3A1#2	S1																				
RX of S3A1#3	S1																				
RX of S3A1#4	S1																				
RX of S3A1#5	S1																				
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RX of S3A1#2	S2																				
RX of S3A1#3	S2																				
RX of S3A1#4	S2																				
RX of S3A1#5	S2																				
RX of S3A2#1	S2																				
RX of S3A2#2	S2																				
RX of S3A1#1	S2																				
RX of S3A1#2	S2																				

(c) Schedule of Sensor 0 (Sink device) (Reception).

Figure 3: Schedules (highlighted slots are the optimal communication slots based on our process).

309 $e_{i,j}$ represents a potential reception event of data i at time slot j : $e_{i,j} = \lambda_{i,j}$
310 is the residual latency, $e_{i,j} = 0$ means that data i can not be received at that
311 time slot.

312 **Example 6.** For the given example, reception parts of the schedule for Sensor
313 1 and Sink are represented respectively in Figure 3b and 3c. For instance,
314 reception part of Sensor 1 represents the possible reception slots for each
315 acquired data of Sensor 3 and 4 with their residual latency.

316 4.3.2. Optimal Choice of Tx/Rx Slots

317 For each device d_i , potential transmission and reception slots are now
318 identified in their schedule table (matrices T_{d_i} and R_{d_i}). The optimization

319 process should now choose the most energy-efficient slots, in order to min-
 320 imize the number of Tx/Rx slots for each device. From the reception part
 321 of the schedule, the algorithm tries to group the receptions from the same
 322 sensor device. For each time slot, it calculates the total number of possible
 323 receptions for each neighbor. The algorithm searches the latest slot in which
 324 maximum number of reception can occur. The latest slot indeed creates
 325 more opportunities for the lower-layer devices. Otherwise, it would force the
 326 lower-layer devices to send the data earlier.

327 In our example, the algorithm analyzes reception part of Sensor 0 (Fig-
 328 ure 3c). It starts by deciding the best communication slot for Sensor 1 and
 329 then for Sensor 2. For Sensor 1, the algorithm chooses $t=7.5$ since the max-
 330 imum of possible receptions is 6 and the latest occurrence of 6 is at $t=7.5$.
 331 Slot occupancy is updated: the slot for $t=7.5$ becomes occupied. Then the
 332 algorithm repeats the same decision process for Sensor 2 and chooses $t=7$,
 333 as the latest possible occurrence of value 4 is at $t=7$. Although $t=7.5$ is the
 334 actual latest maximum, this slot is already occupied, so the communication
 335 slot for Sensor 2 is set to $t=7$. The status of the process after the first it-
 336 eration is given in Figure 4. The algorithm updates the reception part of
 337 the device by defining the unique Rx slot for each concerned data, then it
 338 repeats the same process to decide communication slots for remaining data.
 339 This iteration continues until all data have a defined Rx slot.

	Time (sec)																			
From	0	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6	6.5	7	7.5	8	8.5	9	9.5
S1	3	6	6	6	5	6	4	4	3	4	4	6	5	6	6	6	3	4	4	4
S2	1	4	4	4	3	4	2	2	1	2	2	4	3	4	4	4	1	2	2	2
slot occupancy	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	X	-	-	-	-

Figure 4: Searching for Optimal Rx Slot on Sensor 0
 Slot occupancy: Free -, Occupied X.

340 Our optimization algorithm is a greedy algorithm [9]. Greedy algorithms
 341 are often used in ad hoc mobile networking to efficiently route packets with
 342 the fewest number of hops and the shortest delay possible. Here, the best
 343 solution for Rx slots is found locally on the sink device. Chosen Rx slots are
 344 propagated to the Tx part of lower-layer neighbors in the network topology.
 345 Tx/Rx constraints are then locally updated and the process iterates for those
 346 devices. This top-down process continues until all Tx/Rx slots are defined
 347 for all devices. The finalized reception part of Sensor 0 is illustrated in
 348 Figure 3c. The green slots are the optimal slots found by our algorithm.
 349 Finalized schedules of Sensor 1 and Sensor 3 are also presented in Figure 3.

350 *4.4. Building Complete SCO-PATTERN*

351 Once schedules are finalized after searching optimal communication slots
352 for each device, the last step is to extract Tx/Rx events to obtain the com-
353 plete SCO-PATTERNS.

354 **Example 7.** *Here are the SCO-PATTERNS for the sensor devices of our ex-*
355 *ample:*

356 $P_1 = (\{(0, \{A_T\}), (1.5, \{R\}), (2, \{A_T, R\}), (2.5, \{T\}), (4, \{A_T\}), (6, \{A_T\}), (6.5, \{R\}), (7, \{R\}), (7.5, \{T\}),$
357 $(8, \{A_T\}), (9, \{R\}), (9.5, \{T\})\}, 10)$

358 $P_2 = (\{(0.5, \{R\}), (1, \{R\}), (1.5, \{T\}), (5, \{R\}), (5.5, \{T\}), (6, \{R\}), (6.5, \{R\}), (7, \{T\})\}, 10)$

359 $P_3 = (\{(0, \{A_T, A_H\}), (2, \{A_T, T\}), (4, \{A_T\}), (5, \{A_H\}), (6, \{A_T\}), (7, \{T\}), (8, \{A_T\}), (9, \{T\})\}, 10)$

360 $P_4 = (\{(0, \{A_H\}), (1.5, \{T\}), (5, \{A_H\}), (6.5, \{T\})\}, 10)$

361 $P_5 = (\{(0, \{A_T, A_H\}), (1, \{T\}), (2, \{A_T\}), (4, \{A_T\}), (5, \{A_H, T\}), (6, \{A_T, T\}), (8, \{A_T\})\}, 10)$

362 $P_6 = (\{(0, \{A_H\}), (0.5, \{T\}), (5, \{A_H\}), (6.5, \{T\})\}, 10)$

363 Once SCO-PATTERNS are completed, they are sent by the Gateway to
364 sensor devices to configure them. Sensor devices then execute the given ac-
365 tions periodically, and data flow to the base station where continuous queries
366 are computed. If an application changes its requirements, the configuration
367 process starts again from the beginning.

368 **5. Experimental Platform**

369 In this section, we present the tools used in this study: SoCQ Engine as a
370 continuous query engine and WSN_{et} simulator for the wireless sensor network
371 environment.

372 *5.1. Continuous Query Engine: SoCQ Engine*

373 As a framework for PEMS, we use the SoCQ (Service-oriented Continuous
374 Query) framework [1]. It takes a data-oriented perspective on the pervasive
375 environment: it provides a unified view and access to the various and het-
376 erogeneous resources available in the environment. Pervasive applications
377 can then be created in a declarative way using service-oriented continuous
378 queries over such an environment.

379 Within the SoCQ framework, *XD-relations* (eXtended Dynamic Relations)
380 represent standard relations, that may be updated, or data streams, that
381 continuously produce data. The definition of *XD-relations* can also include
382 virtual attributes and binding patterns that together enable queries to inter-
383 act with distributed services: service discovery, method invocation, stream

384 subscription. Queries may be one-shot queries (like standard SQL queries)
 385 or continuous queries (with a dynamic result, like a stream). Furthermore,
 386 invocations of service methods and subscriptions to service streams can be
 387 parameterized.

388 We illustrate SoCQ in the context of Smart Building. Table 1 shows a
 389 discovery query, the resulting XD-Relation, then a one-shot query and a
 390 continuous query over this XD-Relation. The discovery query (**DISCOVER**
 391 **Services**) searches for sensor services that provide a location, a method to
 392 get the current temperature, and a continuous stream of temperature mea-
 393 sures. The resulting XD-Relation **TemperatureServices** has one **ServiceID**
 394 attribute (here, the URI of a sensor), a **Location**, and a virtual attribute for
 395 **Temperature**. When executed, the one-shot query (**SELECT ONCE**) selects
 396 services located in a given room and retrieve the current temperature by
 397 invoking **getTemperature** method. While executing, the continuous query
 398 (**SELECT STREAMING**) subscribes to the **temperature** stream of every discov-
 399 ered service to build a resulting data stream. If new services are discovered
 400 and/or some services become unavailable, the continuous query automati-
 401 cally adapts the corresponding stream subscriptions.

Table 1: Example of SoCQ queries for a Smart Building.

<pre>CREATE RELATION TemperatureServices (ServiceID SERVICE, Location STRING, Temperature NUMBER VIRTUAL) USING (getTemperature[ServiceId]():(Temperature), temperature[ServiceId]():(Temperature) STREAMING AS DISCOVER SERVICES PROVIDING PROPERTY Location STRING, METHOD getTemperature () : (NUMBER), STREAM temperature () : (NUMBER)</pre>	<pre>SELECT * ONCE FROM TemperatureServices WHERE Location = "501.340" USING getTemperature;</pre>	<pre>SELECT * STREAMING UPON insertion FROM TemperatureServices USING temperature[1];</pre>
--	--	---

402 5.2. WSN Simulator: Modified WSN_{et}

403 In our platform, we integrated the WSN simulator WSN_{et} [10]. WSN_{et} is
 404 a modular event-driven simulator, more precisely a discrete event simulator
 405 (DES). WSN_{et} adopts basic functionality of *DES*: in order to avoid simulating
 406 every time splice, the time line is split into events and no change is presumed
 407 to occur in the system between consecutive events; thus the simulation can
 408 directly jump in time from one event to the next. However, as the PEMS
 409 works on real-time, **we modified the time scheduler** of the WSN_{et} simu-
 410 lator to avoid time scheduling difference: we introduced a time factor to run
 411 experiments in real-time or n -times faster ($\times 10$, $\times 20$...).

412 5.3. Gateway: 3SoSM Gateway

413 In a declarative monitoring architecture (see Figure 1), the **Gateway** is a
414 technical bridge between two environments: it manages interactions and bidi-
415 rectional communication between the **PEMS Query Engine** and the **WSN**. We
416 implemented the 3SoSM principles in a **3SoSM Gateway**. It is implemented
417 in Java, and interacts with the **SoCQ** engine and **WSNet**. 3SoSM Gateway has
418 two primary modules: the **Service Manager**, that manages **SoCQ** services
419 representing available sensor devices (real devices or simulated devices); and
420 the **Subscription Manager**, that continuously analyses application require-
421 ments to generate new **SCO-PATTERNS** for sensor devices when required. In a
422 typical scenario, multiple applications launch continuous queries concerning
423 sensors to the **PEMS**. The gateway manages required parameterized stream
424 requests and, according to the 3SoSM optimization process, generates optimal
425 sensor configurations. With our integrated prototype, we can execute mul-
426 tiple **SoCQ** queries that dynamically subscribe to streams provided by **WSNet**
427 sensor devices. The **Gateway** transparently optimizes the subscriptions and
428 configures the **WSNet** sensor devices with **SCO-PATTERNS**.

429 6. Experiments

430 6.1. Experimental Setup

431 The simulations are performed using the modified **WSNet**. We simulate
432 one part of the topology of our physical platform **SoCQ4Home** deployed in our
433 **LIRIS** laboratory: 70 sensor devices are located at specific positions over
434 a floor of the building (10m × 60m × 4m). The topology is illustrated
435 in Figure 5. The deployed sensor devices have fixed positions during the
436 simulation and we consider that they have enough energy until the end of
437 the simulation. During the simulation process, the initial energy level of
438 sensor devices is set on purpose to emphasize the lifetime difference between
439 both cases.

440 We adopt known pervasive environment communication protocol **Zigbee**
441 **IEEE 802.15.4**, simulated with a **UDG** propagation model (which is a strong
442 simplification for building environments, as it does not take into account en-
443 vironmental effects), 35m transmission range, and basic radio module states
444 for devices (idle, active, sleep, transmission, reception). Calculation of en-
445 ergy consumption is based on CPU and radio components, adopted from [7]:
446 $\mathcal{E}_{device} = \mathcal{E}_{CPU} + \mathcal{E}_{radio} = \mathcal{E}_{CPU} + (\mathcal{E}_{sleep} + \mathcal{E}_{TX} + \mathcal{E}_{RX})$, with $\mathcal{E}_{component/mode} =$

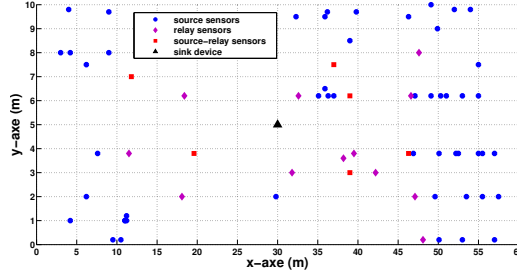


Figure 5: Topology of the network
(Sensor roles are set based on the Application 1 of the scenario given below).

447 $I_{mode} \cdot V_{drain} \cdot \Delta t_{mode}$. This model is a well-known energy consumption calcu-
 448 lation model preferred by many researchers. For instance the paper [11] pro-
 449 poses a temperature-aware task mapping approach for the mapping of multi-
 450 application to NoC-based many-core systems by balancing workloads among
 451 cores. In our study, we adopt a similar approach to calculate the energy con-
 452 sumption of all devices. We implemented sensor devices for **WSNet** so that
 453 they can reconfigure themselves when they receive a new **SCO-PATTERN**
 454 packet, and so that **WSNet** can monitor their simulated energy consumption
 455 while executing sensor actions.

456 6.2. Experimental Scenario

457 To evaluate our approach, we compare 2 types of architecture:
 458 1) an architecture with basic duty-cycle **WSN** devices, requiring a static con-
 459 figuration predefined according to scenario requirements;
 460 2) an architecture with **3SoSM** approach where **WSN** devices can be dynami-
 461 cally configured with **SCO-PATTERNS** generated by the **3SoSM Gateway**.

462 We design four scenarios: “Temperature of Occupied Rooms”, “Comfort
 463 Temperature Range”, “Room occupancy based on CO₂ emission” and “Lu-
 464 minosity of rooms”. Each scenario is performed during one day (1440min).
 465 Here, we present only one of the performed scenarios due to space limitations.

466 **Scenario “Temperature of Occupied Rooms”:** One of the features
 467 of a typical smart building is monitoring temperatures and occupancy of the
 468 environment. Here we suppose that occupancy sensor devices are not always
 469 active but has their own duty cycle for detecting the motion.

470 In this scenario, there exists two applications:

471 **Application 1:** Monitor the temperature of each room with a data acqui-
 472 sition every 15 sec and a latency of 60 sec.

473 **Application 2:** Monitor temperature of occupied rooms with a data acqui-
474 sition every 1 sec and a latency of 4 sec.

475 Here, *Application 1* requests the temperature from all temperature sensor
476 devices with given application requirements. *Application 2* also requests a
477 temperature with a special constraint: it intends to track the temperature
478 only for occupied rooms. For this application requirement, occupancy and
479 temperature sensor devices are needed.

480 For the duty-cycle approach, we adopt a static configuration. In this
481 case, we consider the worst case situation: occupation may be true at any
482 location during the simulation. Based on this constraint, sensor devices are
483 configured with: $p^{acq} = 1sec, p^{tx} = 4sec$ (periodic transmission)

484 In our approach, we propose a dynamic sensor configuration based on
485 the real-time context. To respond to *Application 1* and *Application 2*, sets
486 of SoCQ queries are implemented. For *Application 2*, from the occupancy
487 stream, we extract the location attribute of the occupied rooms. Then, we list
488 the temperature sensor devices that are located in these rooms and implement
489 a new stream query to subscribe to those temperature services with given
490 application requirements. Since these are continuous queries, once a room
491 is not occupied any more or an unoccupied room become occupied, lists
492 are refreshed and new subscriptions or unsubscriptions are handled in real-
493 time. Then, the 3SoSM Gateway creates schedules for each sensor device and
494 generates SCO-PATTERNS to configure sensor devices accordingly.

495 Briefly, *Application 1* receives temperature data from relevant devices
496 under every condition. However, *Application 2* has a remarkable condition:
497 at least one room should be occupied so that it starts to receive temperature
498 data. Here, there are two subscriptions to the same set of temperature sensor
499 devices located in occupied rooms with different application requirements.
500 During the simulation (one day), energy consumption (in terms of joules) of
501 every sensor are monitored periodically and logged.

502 Besides, three more scenarios are performed. Scenario 2 consists of track-
503 ing temperature of each room and requesting more frequently temperatures
504 for rooms that are out of the current comfort temperature range. Scenario 3
505 is based on the occupancy information retrieved from CO₂ emission detected
506 in the room and scenario 4 is related to the luminosity of a classroom. For
507 these scenarios, two applications with different application requirements are
508 executed during a day.

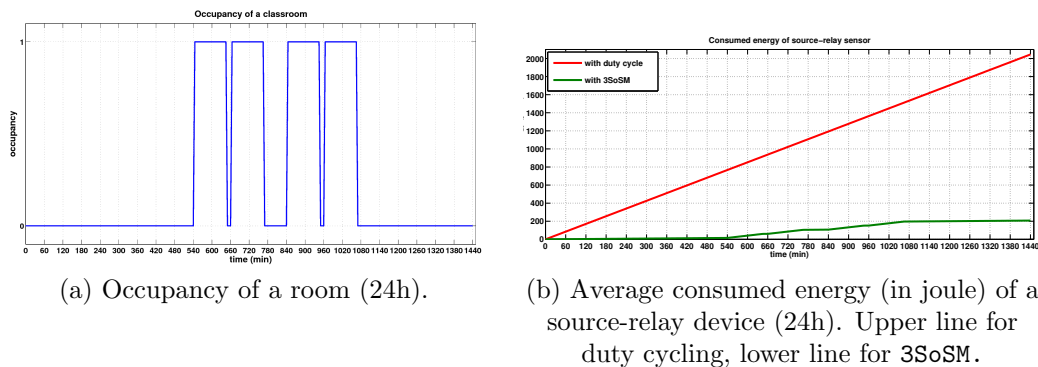
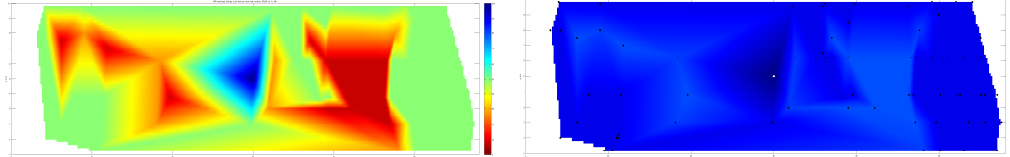


Figure 6: Occupancy information and Energy consumption of the most significant device type: source-relay device with duty cycling and with our approach 3SoSM.

509 7. Results and Discussion

510 During the experiments, energy consumption of each sensor device is
 511 monitored. Figure 6 shows the average energy consumption of source-relay
 512 devices. As a remark, the sink device is not considered as a part of this
 513 energy consumption calculation. Here, we present the results of the first scenario
 514 in detail for one day (1440min). Firstly, the room is not occupied (see
 515 Figure 6a), hence the 3SoSM Gateway creates a schedule and configures the
 516 relevant sensor devices according to that situation. Once the room is detected
 517 as occupied, the 3SoSM Gateway re-creates a schedule and re-configures the
 518 relevant sensor devices. In fact, the 3SoSM Gateway creates a new schedule
 519 and configures sensor devices to adapt to each contextual change in the en-
 520 vironment. Thus, adapting the system to the dynamic context avoids sensor
 521 devices from unnecessary data acquisitions and transmissions. Hence, the
 522 economy of energy can be achieved with this context-awareness, as shown in
 523 Figure 6b.

524 Evolution of the energy consumption for the WSN can be observed with
 525 heat maps as well. Figure 7 represents the heat map of the network based on
 526 the energy level of the sensor devices at the end of the simulation ($t=24h$),
 527 with duty-cycle method (Figure 7a) and with our 3SoSM approach (Fig-
 528 ure 7b), according to the given topology (see Figure 5). With the settings
 529 of the scenario “Temperature of Occupied Rooms”, we observe that our ap-
 530 proach 3SoSM enhances the lifetime of the sensor devices significantly. For
 531 source-relay sensor devices, with given application requirements, 3SoSM ex-
 532 tends their lifetime by 8.9 times on average.



(a) Heatmap of remaining energy at t=24h with duty cycle. (b) Heatmap of remaining energy at t=24h with 3SoSM.

Figure 7: Heatmap of remaining energy with duty-cycle and with 3SoSM.

Table 2: Summary of the Experiments.

Scenarios	Application Parameters				Lifetime (day)	
	Application 1 p^{acq} (sec)	λ (sec)	Application 2 p^{acq} (sec)	λ (sec)	Duty cycling	3SoSM Approach
Temperature of Occupied Rooms	15	60	1	4	15	146
Comfort Temperature Range	20	60	10	20	9	90
Room Occupancy based on CO2	30	120	15	60	11	95
Luminosity of Rooms	30	100	20	80	10	34

533 By applying our approach to given application requirements, we opti-
 534 mize the energy consumption and reduce the unnecessary communication
 535 cost. Obtained results on energy saving and lifetime extension depend on
 536 the application requirements and the context of the application such as tem-
 537 perature and presence. For the current settings, the most unfavorable case
 538 is the situation where every room is occupied during the entire simulation
 539 time. Even in that case, 3SoSM achieves a concrete energy enhancement since
 540 the regular duty-cycle approach does not benefit from latency requirement
 541 which provides a tangible energy saving by allowing grouped transmission of
 542 multiple acquired data.

543 Besides, the details of the other performed scenarios are summarized in
 544 Table 2 for each scenario, application requirements are given and the average
 545 lifetime of source-relay sensor devices are presented. We also obtain a signif-
 546 icant energy enhancement and a lifetime extension by avoiding unnecessary
 547 communication.

548 However, balancing the workload of the network over the sensor devices
 549 like [11] introduces, advanced clustering mechanism like [5] presents, may
 550 further enhance the network lifetime and the obtained results. [5] presents
 551 that with a clustering mechanism and selecting cluster headers in an optimal
 552 way may extend the lifetime of the network better than any other cluster

553 based networks. With more populated topologies and with massive subscrip-
554 tion requests, a discussion about the optimization process appears: in which
555 conditions our approach may fail to find the optimal slots on the schedules
556 (since a slot is reserved for a single device)? In these cases, granularity should
557 be decreased to have enough slots for the sensor devices.

558 8. Related Works

559 WSN are related to several different research domains such as pervasive
560 environment, and smart building systems. In this paper, we give a brief
561 summary of the following research areas that are concerned by our study:
562 energy issues in WSN, sensor network query processing (SNQP), sensor-based
563 Smart Building Management Systems (SBMS).

564 *Energy Issue in WSN.* Wireless devices bring important constraints such as
565 limited battery lifetime. [12] classifies the existing studies on energy con-
566 sumption of wireless sensor devices into 3 subgroups: duty-cycle, data-driven
567 and mobility-based approaches. Our sensor configuration based subscription
568 management approach benefits from scheduled rendezvous of duty-cycling
569 and adaptive sampling/transmission of data-driven approaches.

570 *Sensor Network Query Processing.* The main functionality of Sensor Net-
571 work Query Processors (SNQP) is to handle continuous queries and sensor
572 data streams [13]. [14, 15] propose an adaptive in-network aggregation op-
573 erator ADAGA for query processing on sensor devices in order to filter and
574 reduce the volume of sensor data. The main functionality of ADAGA is to
575 regulate/adjust sensor activities based on energy levels and memory usage
576 of sensor devices. As we propose in our own study, ADAGA is also capable of
577 processing query parameters but the study does not tackle multi-application
578 context and multi-modality of wireless devices as proposed in our own work.

579 We use the Service-oriented Continuous Query (SoCQ) Engine [1] to man-
580 age sensor data streams. SoCQ has a strong advantage from its rivals (es-
581 pecially SNEE [8]) as it supports multi-application contexts. However, it
582 supports neither energy-awareness nor real-time sensor configuration. Our
583 approach provides these features and improvement to the SoCQ Engine.

584 Among available technologies for SNQP, [8] is the closest study to our
585 approach. This study deal with the conflict between the quality of service and
586 sensor acquisition/transmission settings. Authors propose an optimization of
587 application requests and the generation of a query execution plan. Generated

588 execution plan provides a global view of the network and a schedule that
589 shows when to execute a sensor action (sleep, listen, receive/send a packet).
590 In terms of sensor scheduling and parametrization of a query, this approach
591 is highly close to ours. Still, query execution plan covers a single query with
592 a single expectation.

593 *Sensor-based Building Systems.* Some other studies focus on the design and
594 data management aspects as well. Most of those approaches are proposed
595 for a specific application and adopt a static configuration for sensor devices.
596 Sensor-actuator based environment management systems are also studied in
597 this area. [16] mentions that sensor-actuator interactions has a significant
598 effect on efficient building monitoring. Moreover, the study points out that
599 estimation of our daily activities has a crucial role on managing heteroge-
600 neous sensor devices in the environment and provides energy saving and
601 longer lifespans. [5] indicates that clustering and energy efficiency have been
602 considered in wide area of WSN applications and propose a mechanism in
603 which clusters are dynamically built up by neighbor nodes, to save energy
604 and prolong the network lifetime.

605 [17, 18] are the closest studies to ours. [17] presents intelligent building
606 architecture based on a self-adapting intelligent gateway. [18] presents self-
607 adapting algorithms for context-aware systems. These studies propose dy-
608 namic system management while processing user preferences. However, these
609 studies are bounded by predefined building applications and the relation be-
610 tween application requirements and sensor configuration is not established.
611 Besides, these approaches do not benefit from the potential reconfiguration
612 of acquisition and transmission frequencies: sensor configuration stays static
613 during the system lifetime. Moreover, energy consumption within the WSN is
614 not considered as a major issue.

615 [19] is also close to our approach. Author implicates event-triggered dy-
616 namic sensor configuration. The study proposes a ZigBee-based intelligent
617 self-adjusting sensor platform (ZiSAS) that can autonomously reconfigure
618 middleware, network topology, sensor density, and sensing rate based on the
619 environmental situation. However, unlike our proposition, user preferences,
620 application requirements, query mechanism or data stream processing are
621 not handled.

622 Overview of most known existing studies on Smart Building applications
623 is summarized in Table 3. For the categorization of these studies, we ben-
624 efit from the key functionalities of a Smart Building Management System

Table 3: Overview of most known existing studies on Smart Building applications.

Study	Multi-App	Dynamic User Config.	Context-Awareness	Real-Time Sensor Config.	Energy-Aware Monitoring	Query Engine	Experimentation
<i>Doukas et al.</i> [21]	-	-	✓	-	-	-	Real Testbed
<i>Chen et al.</i> [22]	-	-	✓	-	-	-	Simulation
<i>Byun et al.</i> [19]	-	-	✓	✓	✓	-	Real Testbed
<i>Xiang et al.</i> [23]	-	-	✓	-	-	✓	Real Testbed
<i>Rutishauser et al.</i> [24]	-	-	✓	-	-	✓	Real Testbed
<i>Servigne et al.</i> [25]	-	-	-	-	-	-	Real Testbed
<i>Mamidi et al.</i> [26]	-	-	✓	-	-	-	Real Testbed
<i>Kailas et al.</i> [27]	-	-	✓	-	-	-	Real Testbed
<i>Agarwal et al.</i> [28]	-	-	✓	-	-	-	Real Testbed
<i>Preisel et al.</i> [29]	-	-	-	-	✓	-	Real Testbed
<i>Schor et al.</i> [30]	-	-	✓	-	✓	-	Real Testbed
<i>Li et al.</i> [31]	-	-	✓	-	✓	-	Real testbed
3SoSM	✓	✓	✓	✓	✓	✓	Real Testbed and Simulation

625 (SBMS) [20]. The last line of the table is allocated for our approach 3SoSM.
 626 Our research motivation is that the existing approaches are mostly WSN-level
 627 techniques that do not tackle real-time dynamic interactions between applica-
 628 tion continuous queries and the physical environment, in a multi-application
 629 context where sensor devices are multi-modal and requirements are dynamic.
 630 Hence, this lack creates a gap between the computing environment and the
 631 physical environment, that can be both managed by pervasive applications.

632 To address this gap and propose a clear solution for multi-application
 633 monitoring systems, we design a sustainable multi-application monitoring
 634 system architecture for pervasive environments that collects application re-
 635 quirements for sensor data streams and optimizes them into sensor config-
 636 urations. We propose energy-aware dynamic sensor device re-configuration
 637 (as a result of an optimization process) to lower energy consumption while
 638 fulfilling real-time application requirements. Compared to existing studies,
 639 our approach 3SoSM provides a multi-application mechanism and allows dy-
 640 namicity for user configurations and network-aware sensor management while
 641 optimizing the sensor communication for enhancing energy consumption by
 642 real-time sensor configuration.

643 9. Conclusion

644 In this paper, we focus on one of the major challenges of pervasive moni-
 645 toring systems like smart buildings: how to optimize/reduce the energy con-
 646 sumption of the monitoring architecture itself while managing sensor data
 647 streams. Existing studies do not tackle the energy consumption of the moni-
 648 toring system and commonly adopt static configurations for sensor devices.

649 Since application requirements are dynamic with the context, a dynamic sen-
650 sor configuration can be a suitable option to solve this problem. We introduce
651 a sustainable declarative monitoring architecture where we adopt the PEMS
652 principles to separate application development and optimization of device
653 interactions. We present our approach 3SoSM that is based on a WSN schedul-
654 ing mechanism for sensor actions. We propose an optimization algorithm to
655 find the optimal communication time slots. As an outcome, an optimized
656 schedule generates SCO-PATTERNS to configure each device. We introduce
657 our implementation 3SoSM Gateway that supports the optimization process
658 for multiple parameterized subscriptions from dynamic application require-
659 ments. Our approach is validated by the experiments using the SoCQ Engine
660 and a modified WNet simulator. Moreover, our approach gives opportuni-
661 ties to use real testbed data and simulation data which is not so common
662 in the pervasive environment research domain. Smart building applications
663 are our target application, however, this approach can be applicable to other
664 data-centric pervasive environments as well [2].

665 Conflict of Interest

666 The authors declare that there is no conflict of interests regarding the publication of
667 this paper.

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