Interactive Refinement of Distributed Control/WSAN Design for Optimal Building Operation Systems

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ABSTRACT: Control systems which are embedded in a Wireless Sensor/Actuator Network (WSAN) can perform sub-optimally if the control system and WSAN are designed independently. In Building Management System (BMS) applications, such sub-optimal performance can result in lower user comfort and potential control instability. In this paper, we provide a methodology for a WSAN/Control co-design that identifies design requirements that jointly optimize over the WSAN and control parameters, thereby leading to high user comfort in multi-zone building applications. The developed methodology has been illustrated through a distributed and a typical PI centralized lighting control developed using our hybrid/multi-agent platform.

1 INTRODUCTION

Nowadays, networked wireless devices are widely used in many applications, such as habitat monitoring, object tracking, fire detection and modern building. In particular, buildings equipped with BMS, where often large wireless/wired sensor networks are deployed. Designing distributed sensor network applications for such systems face numerous challenges in scaling, delays associated with data collection and energy consumption, which can lead to unstable systems. This instability might also be due to the performance tradeoffs between the control and wireless networks when designing the controller.

Control systems and communication networks are typically designed using different platforms and principles. Control theory requires accurate, timely and lossless feedback data; however, random delays and packet loss are generally accepted in communication networks, particularly in wireless networks. Therefore, the performance of the control model relies on the network performance, due to the distribution and communication based control. From the control perspective, the more knowledge the controller has about the system, the better the control performance is. Additional knowledge about the system is obtained by increasing the number of sensors or sending sensor measurements more frequently. However, this increases the communication burden on the network and cause network congestion. The congestion results in longer delays and more packet losses, which degrades the control performance.

The degradation of the reduced Quality of Service (QoS) at the network level means less user comfort; for example, a communication delay results in a delay to reach the optimal set point (i.e. light luminance). Second, packet losses may cause false alarms or a failure to capture real alarm data.

The objective of our work is to provide a design methodology for control and WSAN systems that improves the building control in relation to user comfort, safety and reliability. These factors are dependent on optimal control parameters and enhanced WSAN QoS.

Our research extends prior work in the area, e.g., (Liu, X. et al. 2005), by exploring the impact of the control performance on the WSAN and vice versa. (Liu, X. et al. 2005) provides a cross-layer methodology to link the standard design layers of an Open System Interconnection (OSI). This methodology ignores the performance of the WSAN and moreover, it does not consider linking the performance evaluation of the different layers which may lead to better control performance but rapidly degrades the performance of the other layers. We have selected the MAC protocol and the Link technique design; we do not consider the network layer because the underlying example uses a point-to-point linking technique. The impact of changing the correlated parameters on both control performance and the WSAN QoS has been considered, with priority given to the objectives of the application, as represented in control requirements.

We propose a methodology that tunes performance using two phases. The first considers tuning control performance to get the best correlated parameter values; for this we calculate the parameter variation boundaries. The second one deals with the WSAN QoS; for this we explore the search population within the boundaries provided previously, to determine the optimal Control/WSAN configuration.

The remainder of the paper is organized as following: Section 2 explains the design optimization approach considering the control and WSAN; moreover the section shows how we can apply this approach on a case study. In Section 3, the case study modeling is discussed. The simulation results, produced from the case study modeling, are discussed in Section 4. Finally Section 5 concludes the paper and highlights the future trends.

2 CONTROL/WSAN REFINEMENT APPROACH

As stated earlier, in modern buildings, distributed controllers over large wireless/wired sensor/actuator network face the challenge of achieving good WSAN performances while designing the control application. The case where both control and WSAN models are designed separately may lead to unstable and sub-optimal implementations. In this research work we assume a high correlation between the performance parameters of both control and WSAN models. For example, if the WSAN has received many requests at a certain moment, this will lead to either delay in responding to the next request (in order to serve all the buffered requests) or dropping some requests which will create unexpected behavior in the environment. In this section we explain our approach for an integrated design of both control and WSAN.

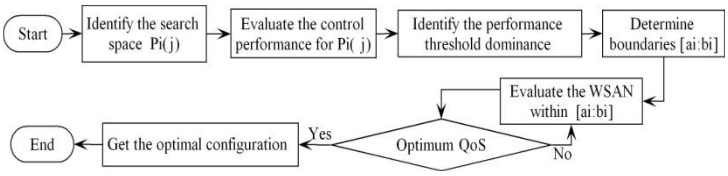

Figure 1. Control/WSAN Co-design Flowchart

Figure 1 shows the flowchart of the approach:

1. First identify the correlated parameters P_i which mutually affect both WSAN QoS and the control performance.
2. Identify the search space for the P_i with acceptable values $P_i(j)$.
3. With the assumption that the control performance has higher priority, evaluate the control performance (Mean Square Error "MSE") according to the identified search space.
4. Evaluate the MSE according to $P_i\ (j)$, which indicates the value for P_i at instance j.
5. Repeat step 4 until obtaining acceptable control performance, and hence identify the boundaries $[a_i,b_i]$ for each parameter P_i.
6. Evaluate the QoS of the WSAN within the identified boundaries $[a_i,b_i]$.
7. Repeat step 6 until the QoS equals the predefined stopping criteria for the WSAN.

2.1 *Lighting Example: Parameterizable and Predictable Distributed Controller*

This section introduces our new Parameterizable and Predictable Distributed controller (PPD-Controller) for automated lighting systems (Mady, A. et al. 2010). The PPD-Controller offers a distributed solution and aims to increase the control reliability, scalability, resource sharing and concurrency.

An open office area with a typical architecture is considered, as shown in Figure 2. It contains 10 controlled zones; each zone contains one artificial light, one light sensor and one Radio-Frequency Identification (RFID) receiver. There are 4 windows/bindings on the right and left boarders of the open area and a fix number of predefined person positions.

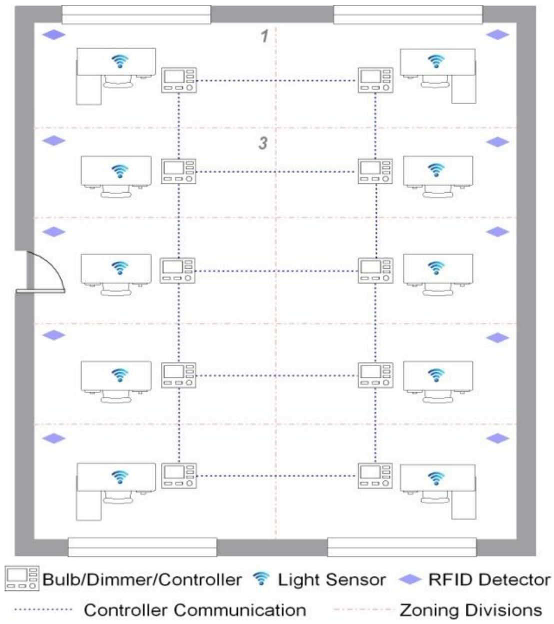

Figure 2. Model Specification

The lighting system integrates blinding and lighting controls. It also simultaneously optimizes the light luminance and blind position, depending on the user preferences and the power consumed by the artificial light and the blinding actuators.

As a summary, the lighting control scenario behaves as follows:

1. The user can switch on/off the automatic lighting system for several zones, or for all the system through a technician.
2. The users provide their preferences (light luminance and blinding position).

3. A person is tracked in each zone using for example RFID; his preferences are ignored whenever he leaves his zone.
4. A local optimization engine receives the user preferences and sends back the optimal settings.
5. The local controller controls the artificial light and the blinding actuators in order to reach the user preferences considering the daylight luminance and the light interferences coming from the adjacent zones.

2.2 *Correlated Parameter Identification*

Through studying the correlated parameter space of the PPD-Controller/WSAN, we have identified that the Sensor Sampling Period (*SSP*), Controller Sampling Period (*CSP*) and Zone Number (*ZN*) are the correlated parameters P_i; in contrast, the centralized controller has only a single correlated parameter, *SSP*.

However, other parameters may affect the WSAN or the control separately; for example, the sampling period for the RFID affects the WSAN QoS but it does not affect the controller. As it is handled by the controller in an event-based model, the controller considers only the occupant presence and not the frequency of the sampling period. We have found, in general, that in the distributed approach the P_i depends on the control strategy, and in the centralized control model the P_i depends more on high *SSP* values.

3 CONTROL AND WSAN MODELING FOR THE PPD-CONTROLLER

In this section, we briefly describe the control and the WSAN models.

3.1 *Control Modeling*

Figure 3 shows the model of a local controller and its interactions with the environments. The preference solver receives the user preferences for each zone, sends the optimal light luminance and blinding position back to the optimization engine. This latter solver uses Genetic Algorithm/Simulated Annealing (GASA) algorithm (El-Hosseini, M.A. et al. 2008) in order to calculate the optimal actuation settings, and then sends them back to the PI-Controller. The PI-Controller predicts the next actuation setting for the lighting level in a closed-loop fashion (Kolokotsa, D., et al. 2008), using Eq. 1. It actuates the artificial light and the blinding position according to the optimum settings. Whenever preferences change, the optimization step is updated; otherwise, the PI-Controller actuates based on the external light and the light interference. The Light/Blinding Occlusion Preference Solver agent is used to provide the intermediate solution between several luminance/glare preferences in the same controlled zone. It applies a Low Pass Filter (LPF) in order to prevent exceeding a predefined threshold (700 Lux for luminance and 100% for the blinding position). The control equations are given by:

$$A(t+1) = A(t) + \theta \qquad (1)$$
$$U(t) = A(t) + E(t) + I(t)$$

$$\theta = \begin{cases} \gamma - \dfrac{\beta}{\rho} if[U(t) - S(t)] > \varepsilon \\ \dfrac{\beta}{\rho} - \gamma if[S(t) - U(t)] > \varepsilon \\ 0 if|S(t) - U(t)| \le \varepsilon \end{cases}$$

In equation (1) we use the following notation: A(t) is the actuation setting for light/blinding actuators, E(t) is the daylight intensity (Lux), I(t) is the interference light intensity (Lux), U(t) is the sensed light intensity (Lux), S(t) is the optimal preference settings, ε is the luminance level produced from a single dimming level (70 Lux), β is the maximum light intensity error (700 Lux), γ is the minimal light intensity error (0 Lux) and ρ is the total number of dimming levels (10 levels).

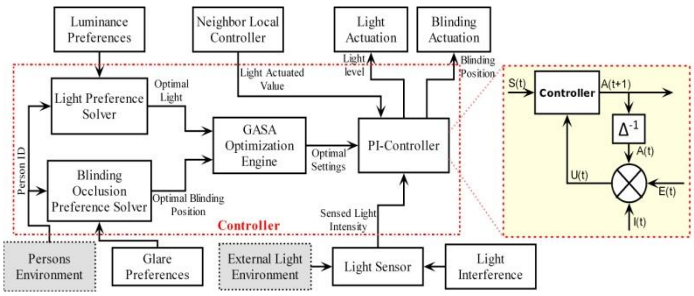

Figure 3. Control Model

3.2 *WSAN Modeling*

In order to evaluate the WSAN performance for the PPD-Controller, we have modeled the WSAN using the VisualSense tool (The Ptolemy Project). We have also considered the Tyndall (Tyndall National Institute) sensor node as a reference for the model parameters. The Time Division Multiple Access (TDMA-based) MAC protocol (Liu, A., et al. 2005) is used in the contention-free period, which leads to a free collision probability. Figure 4 shows the WSAN model used for evaluating 4 zones (1, 3, 4, 5) (Fig. 2). The PPD-Controller in zone 3 has been selected to be evaluated as it constitutes the bottleneck in the model, since it is the most heavily used due to its communication with the other 3 controllers (1, 4, 5), their RFIDs and sensors. In relation to the

WSAN performance, the Response Time (Delay) for the network has been considered as the QoS metric (Demirkol, I., et al. 2006).

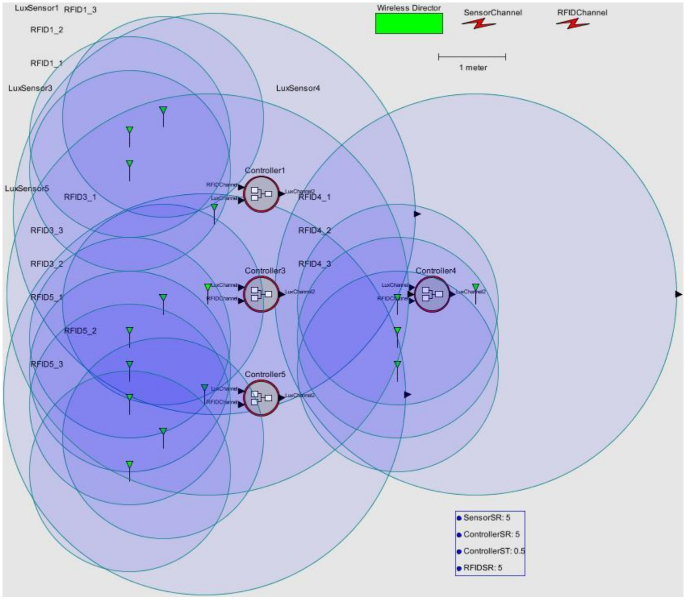

Figure 4. PPD WSAN Model

The Response Time (Delay) reflects the user comfort, whereas we have considered it in the control evaluation metric as well.

When modeling the WSAN for the PPD-Controller, we distinguished four models:
Communication channels model: 2 channels are considered for the wireless communication, one channel for light sensors and the local controllers (Zigbee band, i.e. 2.4 GHz) and other for the RFIDs (RF band, i.e., 324 MHz). The power propagation factor in the communication channels is $1/4\pi r^2$, where r is the distance between the transmitter and the receiver, and the loss probability in each channel is 2%.

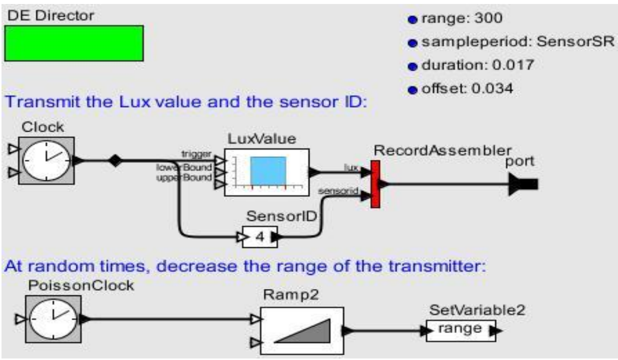

Figure 5. Light Sensor Model

Light sensor model: The sensor sends the Lux measured value and the sensor ID to the controller using a fixed sampling rate and frequency offset, as shown in Figure 5. The sensor coverage area is 3 meters (distributed in sphere area) and its power transmission is 0.1 watt/m^2. In order to show the effect of the battery discharging on the sensor transmission range, we have assumed that the range is decreasing by 0.1 meter each event that follows Poisson distribution with mean time equals to 20 times the sensor sampling rate.

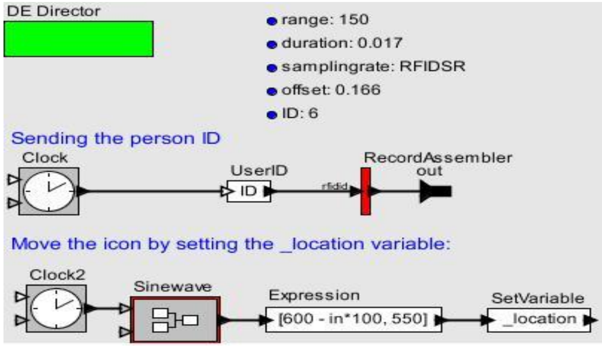

Figure 6. RFID Model

RFID model: The RFID detection range is 1.5 meters and its power transmission is 0.1 watt/m^2. As shown in Figure 6, the RFID sends its ID with a fixed sampling rate and frequency offset. Moreover, the movement of the RFID is modeled as a sin wave sampled every 0.3 minute.
Controller/Receiver model: In this model, shown in Figure 7, we have considered the received packets number, buffer size and the controller duty cycle. However, the controller service time is fixed per received packet. The communication between the neighboring controllers also uses the sensor channel.

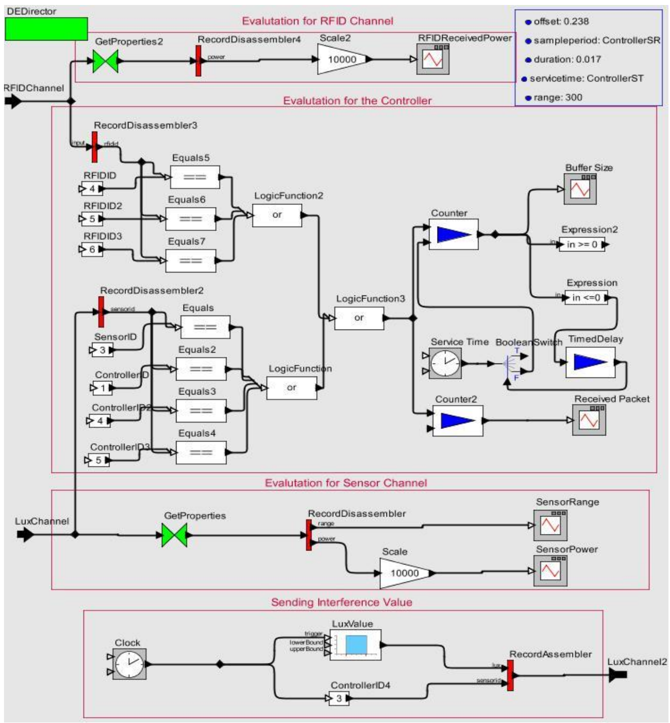

Figure 7. Controller/Receiver Model

4 EXPERIMENTAL RESULTS

In this section we describe the results of applying the proposed methodology to design the PPD-Controller and its underlying WSAN model. It integrates for comparison purposes, the results when considering the design performances for a typical PI centralized controller. The study also looks at the impact of the zones number on the Control/WSAN performances.

We note that the PPD-Controller imposes some constraints that help to restrain the evaluation space; for example, a design constraints should be defined in order to determine the value of *CSP* that corresponds to each *SSP*. Mainly, the *CSP* is used to exchange the actuation values, so that the controller can detect the interference coming from other zones. Therfore, the controller changes its actuation value only when it receives a new sensed value from the sensor, i.e. $CSP \geq SSP$. In this experimintal design, we consider the worst case from the WSAN side, i.e. $CSP \equiv SSP$.

4.1 *Control Refinement*

In order to evaluate the control performance, the MSE between the sensed value and the set-point is used as follows.

$$MSE = \sum_{a=1}^{N} \frac{\sum_{k=1}^{M} (U_a(k) - S_a(k))^2}{M.N} \quad (2)$$

Where: N is the total number of zones; M is the total number of samples.

In relation to the *SSP* values and the corresponding *CSP*, we have considered typical set of values: {1,5,10,15,20,25,30,35,40,45,50,55,60}. For the zone number, *ZN* varies from one single zone to the maximum number of zones considered in the design specification (i.e. 10), $ZN \subset \{1,2,4,8,10\}$.

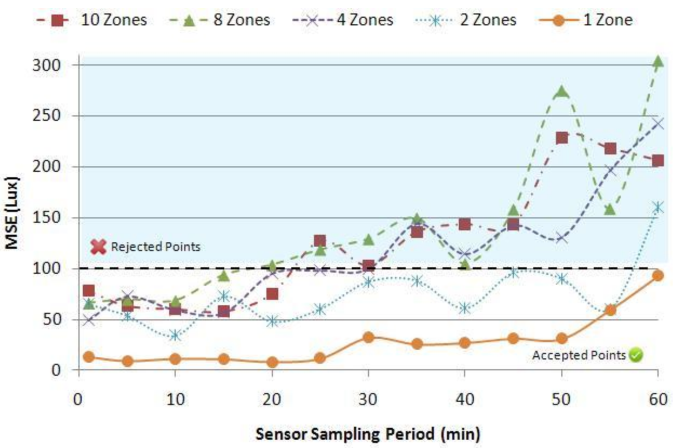

Figure 8. PPD Control Evaluation

Figure 8 shows the control evaluation for each parameter. The satisfaction range for *SSP* and *CSP* is determined by the boundaries shown in Table 1. In this case, we have assumed a threshold dominance of 100 Lux for the MSE.

Table 1. $P_i(j)$ ranges at control refinement stage

	$[a_i,b_i]$ (min)
PPD (NZ =1)	[1,60]
PPD (NZ =2)	[1,55]
PPD (NZ =4)	[1,30]
PPD (NZ =8)	[1,15]
PPD (NZ =10)	[1,20]
PI-Centralized (10-zones)	[5]

Figure 9 shows the experimental results for a typical centralized PI controller controlling the lighting system for 10 zones. By assuming the same threshold dominance used previously, the satisfaction point for *SSP* equals 5 min (Table 1). Therefore, the PPD design offers a wider range for the SSP, which can reach 20 min, compared to the centralized option. This will certainly lead to better WSAN design.

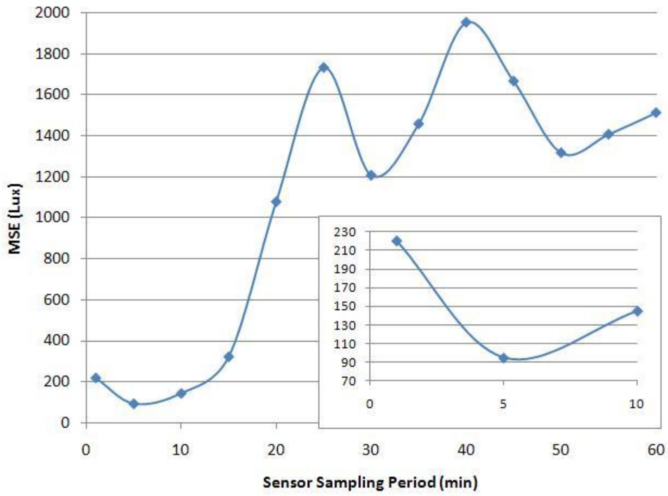

Figure 9. PI Control Evaluation

We note that the wavy shape appearing in some ranges (Figures 8, 9) is due to the acceptable variation margin that equals to one dimming level in the PI-Controller (70 Lux).

4.2 *WSAN Refinement*

After identifying the satisfactory range resulting from the previous step, the WSAN design is refined in order to reach the optimal QoS.

As mentioned earlier, our aim is to provide an optimum Control/WSAN co-design that maintain the maximum user comfort. To achieve this, the best WSAN QoS candidate is the Network Response Time (NRT). In our wireless network model, we have assumed that there is no packet drop, which means that the response time at the controller equals to the buffered packet multiplied by the controller service time (0.5 sec).

Large *SSP* values result in better WSAN performance and longer battery life. On the other hand, large *SSP* values do not affect the *NRT* and the user comfort, since it is within the optimal range. Therefore, we have considered the upper limit for each parameter.

As mentioned earlier, some parameters affect only the WSAN, which is the case for the sampling period of the RFID (*RFSP*). Therefore, we vary *RFSP* under an accepted stopping criteria (e.g. *NRT* = 1 sec).

Table 2 shows the experimental results for the different WSAN models and the corresponding *RFSP*. Through studying Table 2, we can conclude that in the centralized control strategy you have to accept slow response in the person movement update which may lead to user discomfort, as the user needs to wait for 15 sec to get his preference. However in the PPD control strategy, he needs to wait a maximum of 3 sec.

Table 2. *WSAN* refinement stage

	***RFSP* (sec)**
PPD (NZ =1)	2.5
PPD (NZ =2)	2.5
PPD (NZ =4)	3
PPD (NZ =8)	3
PPD (NZ =10)	3
PI-Centralized (10-zones)	15

5 CONCLUSION

In this article, we have provided through our hybrid/multi-agent platform a refinement methodology for improving the Control/WSAN performance within the building automation domain. Such improvement plays a key role in guaranteeing properties such as safety, accuracy, stability and reactiveness, which greatly impact user comfort. The developed methodology can configure the Control/WSAN-correlated parameters, and thereby reach an efficient configuration. The approach has been tested on a PPD-Controller and PI centralized controller used for lighting systems. The impact of changing the correlated parameters on both control performance and the WSAN QoS has been considered, where priority is given to the objectives of the application, as represented in the control requirements.

As future work, we intend to apply our methodology to Heating, Ventilating, and Air Conditioning (HVAC) system, as this presents more interesting challenges in relation to user comfort and control stability. We also aim to deploy a demonstration of the developed system in the Environmental Research Institute building (ERI), which is the ITOBO Living Laboratory (Environmental Research Institute). The benefit of cross-layer modelling for distributed control constitutes an important research topic that we also intend to pursue in future work.

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