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Leveraging BIM Interoperability for UWB-based WSN Planning

Riccardo Tomasi, Francesco Sottile, Claudio Pastrone, Mohammad Mozumdar, Anna Osello, Luciano Lavagno

***Abstract*—Wireless Sensor Networks (WSNs) are a key part of the Internet of Things (IoT) vision which aims at bridging together the physical and the digital worlds in several application domains. In the Building Automation field WSN are widely adopted for energy optimization, safety and security purposes and could greatly benefit from existing information which is already available in pre-existing Building Information Models (BIM). Such BIMs are normally developed during the building design phase and re-used continuously during the construction and operation phases of the building life-cycle. In current deployments, however, due to lack of interoperability such information must often be re-collected and re-inputed by WSN commissioning specialists. Open development and planning tools and methodologies can play a key role in fostering interoperability and convergence of BIM and WSN systems. This paper aims at demonstrating how increased interoperability between WSN development-support tools and BIM systems could provide advantages to developers, integrators, domain specialist and BIM users. The methodology is validated by applying a newly proposed tool exploiting BIM interoperability to support the planning of the topology of a WSN based on Ultra Wide Band (UWB) technologies. The proposed approach is evaluated through a small-scale experimentation held in a historical building in Torino (Italy).**

***Index Terms*—BIM, WSN, Development-support Tools, Connectivity, 3D Positioning, Indoor Positioning, UWB**

I. Introduction

Recent developments in technologies for constrained low-power embedded devices have enabled the possibility to enrich any physical objects with processing and communication capabilities at a low cost, thus making real applications of Wireless Sensor Network (WSN) sustainable also at a large-scale. While WSN in past years were normally deployed for a pre-defined purpose, on-going evolutions are also paving the way towards more open, general-purpose paradigms such as the Internet of Things (IoT) where objects can autonomously discover other objects, services and physical-world entities, participating autonomously in multi-purpose, cross-domain tasks [1]. Such vision is still however not fully feasible due to the challenge of achieving full interoperability among a large number of heterogeneous technologies used to develop IoT devices and Internet-oriented services and to support collaboration processes, especially when considering the broad number of existing, legacy systems which are today in operation in the different IoT application domains.

The Building Management domain has been an early adopter of IoT/WSN technologies e.g. to enrich legacy Building Management Systems (BMS) with self-configuring, intelligent, Internet-enabled sensors and to ease integration with Internet-oriented services and user devices.

This adoption has also economical reasons. Studies show that building sub-systems, e.g. lighting, heating, ventilation, air-conditioning, etc. cover for a relevant share of the total energy consumption in developed countries and that, especially in large public buildings controlling such operations effectively can significantly reduce energy consumption, still taking into account the safety, security, privacy, health and comfort constraints of the occupants and maximizing operational productivity of the building management staff.

In recent years, professionals involved in building design, construction and maintenance are progressively transitioning towards BIM (Building Information Modeling) solutions to keep and exchange information about buildings. The key advantage of BIM tools compared to previous CAD (Computer Aided Design) solutions is that the building under design is not anymore a simple 3D drawing, but it is a complete physical and functional model of the building which includes information about materials, sub-systems and their expected usage. Such model can be processed and used throughout all the life-cycle of the building, from design, to construction, to use, to decommissioning. Since the context of operation of IoT solutions can depend significantly on the deployment conditions, information stored in BIM solutions, if accessible and inter-operable, could provide valuable input to any IoT system. We can easily expect that multi-disciplinary teams will be involved in specifying, designing, implementing, deploying and maintaining these new BMS solutions. As depicted in Fig. 1, these teams could involve architects as well as civil, electronics and telecommunication engineers and software developers, all with a common need to share a unified representation of the WSN node placement, in order to optimize sensing, actuation, communication, power supply, maintenance access and so on. BIM could surely be extended to foster collaboration among professionals in the ICT and construction domains, if properly supported by tools easing interoperable and automatic access to building information.

This paper aims at demonstrating a use-case of convergence between BIM and WSN development support tools, by verifying the possibility of integrating the Hy-Sim framework [2] with a set of open-source BIM tools. The resulting component

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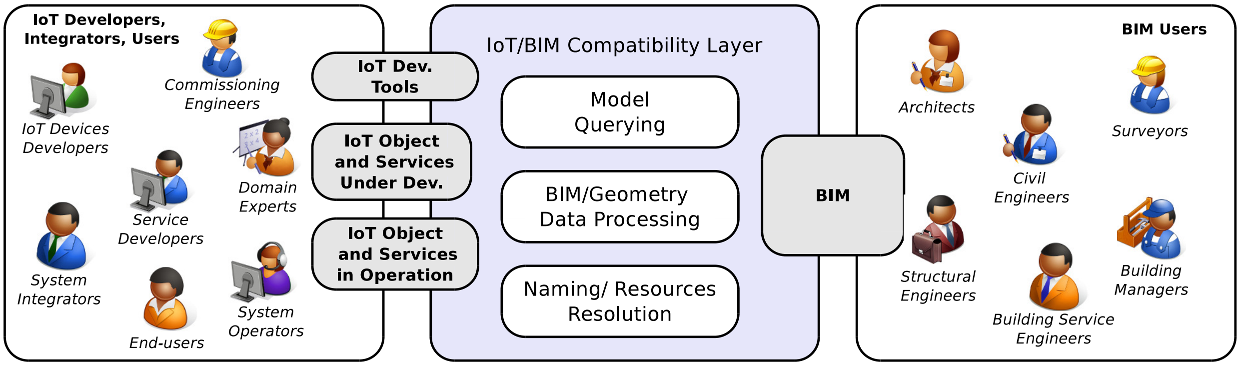

Fig. 1. BIM as a tool to support collaboration between professionals in the ICT and construction domain

is used to foresee the ranging behavior of a WSN based on Ultra Wide Band (UWB) technology used for indoor positioning. The estimations of the tools are then validated, comparing with a small-scale experimental evaluation.

The remaining of the paper is organized as follows: Sec. II describes related work, providing an overview of state-of-the-art solutions and technologies adopted to exploit interoperability between BIM and WSN development tools; Sec. III discusses the proposed methodology and its underlying ideal reference architecture; Sec. IV describes a proof-of-concept which has been realized to assess the preliminary feasibility of the proposed methodology; Sec, V describes the small-scale experimental evaluation performed to validate the framework; Sec. VI draws conclusions and outlines future work.

II. Related Work

Various methodologies and development tools have been proposed to tackle the intrinsic complexity of coding and deploying WSN applications running on constrained, heterogeneous, distributed WSN systems.

WSN tools cover the whole life-cycle of WSN development, supporting various tasks such as requirements elicitation and analysis [3], development [2], testing [4], integration [5], deployment in the end-user scenario [6], maintenance, monitoring and debug [7], etc. Throughout all stages, especially in scenarios where WSN are integrated with other large-scale IoT eco-systems [5], [8], [9], [10] or processes [11], ensuring future interoperability of WSN solutions is the main challenge. In order to cope with the growing complexity and composability needs of end-user applications, a number of solutions follow holistic development/integration approaches. Such approaches consider since the early design time how parts of the developed WSN solutions will be discovered, accessed and controlled from within the overall IoT network infrastructure [12]. These solutions often follow a model-driven approach [13] and eventually integrated in the development loop behavioral simulation of WSN nodes [14] or sub-components [15]. Some of them, such as [2], ease convergence of WSN with web-oriented systems by enabling the model-driven development of RESTFul WSN applications. Such tools allow developers to start from a design contract coded in the WSDL 2.0 standard definition language [16] and generate working WSN application code automatically compatible with the CoAP stack [17]. Other approaches [18] focus more on gateways as the place where dedicated heterogeneous WSN technologies are discovered and exposed towards the IoT, eventually following standard integration patterns [19].

When the developed WSN solution approaches the deployment phase, planning aspects grow in importance, as a cost-effective and reliable deployment impacts significantly future operation and maintenance costs of the WSN system. Such tools, given the characteristics of the WSN platform under deployment, aim at optimizing the deployment in terms of cost, reliability, resilience to failure. On the one hand they must satisfy the end-user need e.g. in terms of required number and distribution of node placement points. On the other hand, they must respect the scenario constraints such has the number and position of access points with permanent connectivity, etc.

Existing planning tools focus on various optimization aspects such as radio connectivity [20], sensors coverage [21], or positioning performance [22]. A number of such planning tools are tailored for the building automation domain [23] and require an underlying model of the building in order to properly forecast and optimize the behavior of the WSN under given conditions.

The need for sharing and working collaboratively on common Building Information Model (BIM) is well-known in the BIM research community [24]. Due to the organizational synergies provided by BIM-centered approaches, such processes are rapidly being adopted by architects, building engineers and overall in the construction industry and by major building management services providers, also thanks to several standardization actions [25].

Due to the unprecedented amount of context information which can be retrieved in BIM, a number of works [26], [27], [28], [29] have started to consider the importance of convergence between BIM and IoT information models [30] also starting to identify the potential advantages deriving from the consideration of BIM information since the development stages of WSN/IoT applications [31].

Although this work is still at the stage of conceptual framework, it represents an interesting area of research and development for upcoming years.

III. Proposed Methodology

Fig. 2 depicts an ideal methodology and its underlying ideal reference architecture to exploit interoperability between BIM and WSN development tools for WSN planning purposes. Within this work a proof-of-concept has been realized to assess its preliminary feasibility, as described in the following Sec. IV.

The process starts from a pre-existing BIM model, which is made available through standard BIM interfaces (e.g. IFC-compliant APIs) by a *BIM Server* or as a shared static BIM model. A dedicated software service named *BIM Adaptation Layer* (BIM-AL) is in charge of easing interoperable access to information stored in the BIM by IoT systems and tools. The BIM-AL, beside exposing the standard BIM model in a controlled fashion, is also needed to keep deployment-specific meta-data such as the mapping between custom classes used in legacy BIM models and general-purpose classes/concepts used in IoT applications. Since in general the BIM should

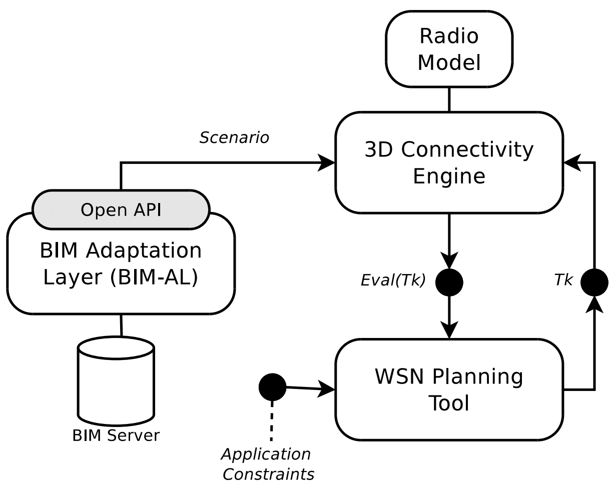

Fig. 2. The Proposed Methodology for WSN Planning

already encode in an interoperable fashion all the relevant building-related information, ideally the BIM-AL component would be transitional and should disappear in the long-term. However, this will be likely impossible both due to the very broad scope of IoT applications and the flexibility offered by BIM tools to architects, which entails that often the same parts can be described in different ways within different BIM models, thus leaving the need for a dedicated integration layer in any practical application. For such reason, the proposed methodology assumes that the BIM-AL component will be designed as a wrapper around standard BIM API [32], providing the ability to host deployment-specific, or IoT-specific extensions and annotations. In general, the BIM-AL shall be accessible to general purpose IoT services and applications; consequently, according to current trends in IoT applications, it should expose open, possibly RESTFul APIs, which can be easily linked with other open systems e.g. by means of semantic annotations. In the case of planning applications, the BIM-AL is used jointly with a *3D Connectivity Engine* which accesses the geometry of walls and furniture, together with associated physical properties which may influence radio capabilities e.g. material-related information. The Engine embeds a number of dedicated configurable Radio Models which are capable to simulate radio link properties for any tuple of devices installed in the building. Radio Models are different for each radio technology, in order to cope with the dependence of radio performance upon operating frequencies, employed modulation schemes, channel coding, etc.

The Engine is accessed by a *WSN Planning Tool* which is provided by engineers in charge of planning/commissioning with a set of *application constraints*. Such constraints include e.g. the minimal set of points where WSN nodes should be placed to ensure that physical parameters of interest are properly monitored, the list of locations where a permanent power source and LAN/Internet connectivity can be provided to WSN Gateways, etc.

In order to meet all requirements and constraints, the proposed methodology follows an iterative optimization approach. Starting from an initial solution T_k, generated manually or randomly, the tool iteratively generates new topologies ($T_{(k+1)}$,$T_{(k+2)}$,...) which are evaluated for feasibility through the 3D Connectivity engine and progressively optimized to ensure that planning metrics are optimal (e.g. minimum number of WSN devices are installed), still respecting application and non-functional constraints e.g. estimated link quality is sufficiently good for all links in the WSN, consumption of battery-powered devices is fairly balanced, etc.

The final output of the process is the optimal WSN topology $T_{opt.}$ and a simulated radio model $eval(T_{opt.})$ which estimates how the WSN should perform in its operational environment.

IV. Proof-of-Concept

In order to partially validate relevant parts of the proposed methodology, an experimental proof-of-concept has been developed, mimicking the process needed to plan the deployment of a WSN used for 3D indoor positioning services.

In the chosen reference application a set of UWB-based WSN nodes are deployed to precisely and continuously estimate the position of mobile WSN nodes (e.g. small mobile robots, drones, people carrying UWB transceivers, etc.) within the building. UWB-based WSN nodes are considered more and

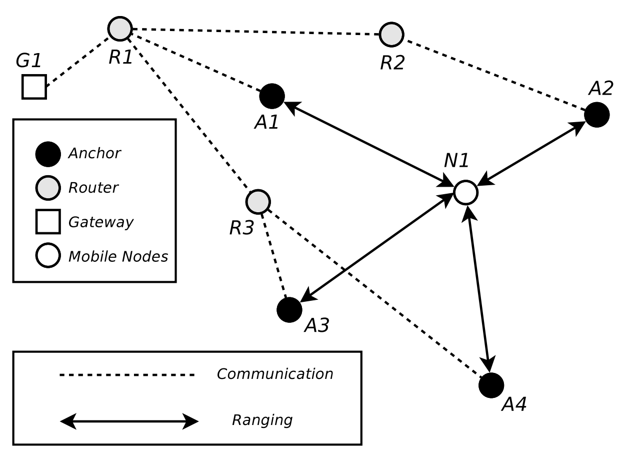

Fig. 3. An example of topology for the reference WSN Application

more relevant for these applications because of the decreasing cost of UWB transceivers and the very high precision (down to a few centimeters) in locating objects in complex 3D indoor spaces where GNSS technologies cannot work properly due to lack of LoS visibility towards GNSS satellites.

As depicted in Fig. 3, this kind of WSN employs a number of WSN end devices whose position is known a-priori, called *Anchors*. Anchors (A) are able to perform ranging estimations towards mobile nodes (N) using Time of Arrival (ToA) estimations. In a centralized localization approach, ranging measurements are then forwarded in multi-hop fashion using an ad-hoc backbone of WSN routers (R) and conveyed to a central positioning server by one or more Internet-connected gateways (G).

By processing ranging measurements, the positioning server computes the position of all mobile nodes and makes it available to end-user applications.

Based on this positioning application an experimental proof-of-concept has been as depicted in Fig. 4. A pre-existing BIM model of the site [33] developed in Revit [34] has been initially analyzed and processed through open tools, to asses the feasibility and the main challenges in developing a full fledged BIM-AL.

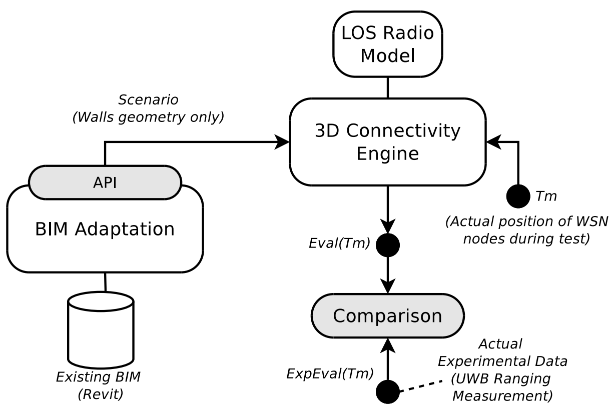

Fig. 4. Overview of the proposed proof-of-concept

After having successfully extracted the geometry of walls and verified the possibility of retrieving material information from the model, a simple 3D Connectivity engine has been developed, implementing a Line-of-Sight (LoS) radio model able to identify and track the number of obstacles (walls, furniture) between any two points of the model.

The 3D Connectivity engine has been then used to estimate the ranging performance of a UWB-based WSN network with four anchor points (A) in 30 pre-defined measurement points (P). The same set-up has been physically reproduced, evaluating the same performance metrics experimentally and comparing them with the results expected from the estimation.

Results of such comparison are presented and discussed in Sec. V.

A. Accessing BIM data through open tools

The following process has been followed to validate the feasibility of programmatically extracting the required walls and furniture geometry information from the available BIM. The result is a first working demonstration of a simplified BIM-AL component which confirms the feasibility of this approach and sets the initial base for future implementations of fully-fledged BIM-AL systems.

The available Revit BIM model can be exported in various available formats which have been analyzed for compatibility. After analysis, the standard IFC4 format [35] has been selected and verified through a third-party tool, namely Solibri Model Viewer [36] to ensure that all the walls geometry and furniture were still accessible in the model. Snapshots of the model, as shown in the viewer, are provided in Fig. 5. In order to evaluate the possibility to host the model in an open web-oriented BIM environment, the result IFC BIM model has been then imported into a running instance of BimServer [37], and queried both through its embedded query engine and externally via SOAP calls.

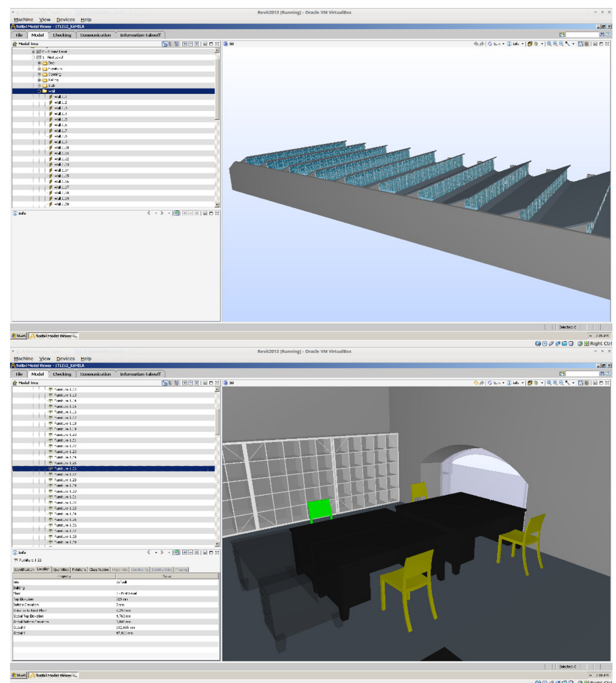

Fig. 5. Views of the BIM model in Solibri Model Viewer

Subsequently the IFC model has been imported in the popular open 3D modeling tool Blender [38] as shown in Fig. 6. Since the direct import of the IFC model was not performed correctly due to version incompatibility issues, an intermediate conversion via IfcOpenShell [39] has been performed.

Since Blender focuses on 3D modeling only, some BIM information is lost in this conversion; however, the conversion does not hamper the unique BIM identifiers of the various 3D objects in the model, and it is thus possible to work in Blender with the correct geometry of walls and furniture, tracing back to the original BIM by querying through the unique identifiers when full BIM information is needed.

At this point, users can specify connectivity targets i.e. anchors and nodes either directly in the Blender 3D environment (manual placement) or programmatically from a list of 3d coordinates stored in files and loaded leveraging the python-based scripting capability embedded in Blender [40].

In order to practically implement the 3D Connectivity Engine, a dedicated C++ ray-tracing component has been developed using the CGAL library (Computational Geometry Algorithm Library) [41] and integrated with the Blender Scripting engine via direct calls to its open API.

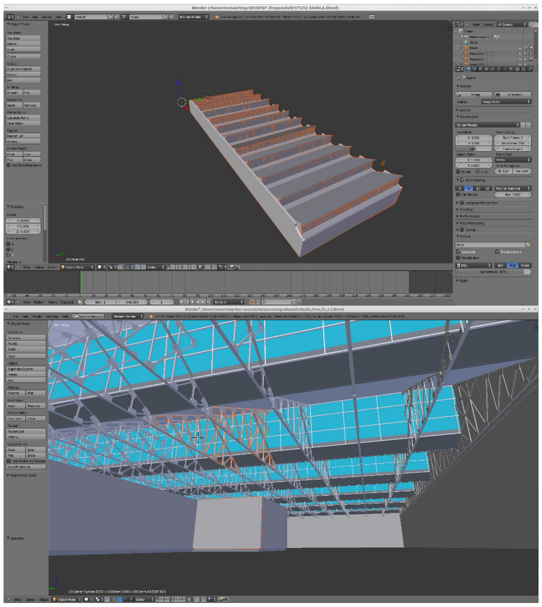

Fig. 6. Views of the BIM model in Blender

B. The 3D Connectivity Engine

As described in Algorithm 1, the algorithm iterates through all radio links of interest and evaluates estimated euclidean distances by exhaustively searching for LoS obstacles i.e. in the Eval3D function. Such function includes a simplified UWB radio connectivity model correlating the presence of obstacle and distance with expected precision. The approach

Algorithm 1 3D Connectivity Engine algorithm

```
R ← []
for each A_i do                ▷ Iterating through all anchor nodes
    for each P_j do            ▷ Iterating through all meas. points
        R[i, j] ← EVAL3D(A_i, P_j, Building)
    end for
end for
```

of performing exhaustive search across all possible obstacles while evaluating a single radio link has been selected as it is the simplest way to realize the described proof of concept. However, this approach will not be scalable in large scale scenarios, since the number of single-links evaluation depends on the product number of anchors, measurement points and elements in the building, which can be very large.

With the current approach, consequently, the test would be too computationally complex to handle the chosen building model on a normal development machine in reasonable time. For this reason a number of hierarchic approaches are being considered to improve the scalability of the computation.

Optimization of the scalability of the radio model evaluation approach is however beyond the scope of the feasibility evaluation. For this reason, just for the purpose of this work the tool has been this instead applied to a scaled-down version of building model which only includes the two rooms of interest for the experimental evaluation, as shown in Fig. 7.

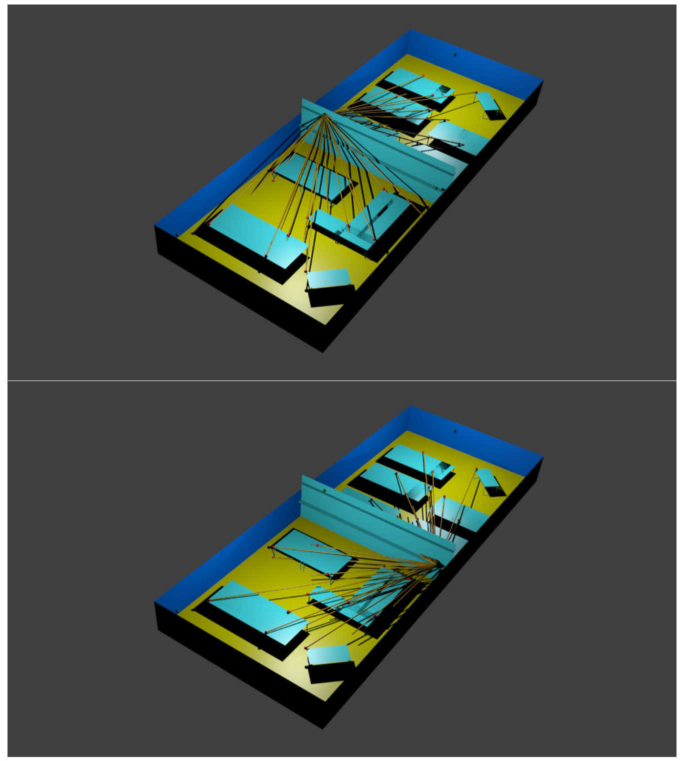

Fig. 7. UWB links evaluated by the 3D connectivity engine

V. RESULTS

The validation has physically taken place in two office areas of the Istituto Superiore Mario Boella[1] (ISMB) building, an open-space built inside a renovated area of the OGR (Officine Grandi Riparazioni) historical industrial site in Torino (Italy), used for assembly and maintenance of trains between 1890 and 1970.

For the validation, 4 anchor nodes (A1, A2, A3, A4) have been installed in fixed position and 30 pre-defined measurement points (P1, P2, etc.) have been chosen at various heights i.e. floor-level, on desks, on cabinets, etc. Fig. 8 shows the actual position of anchors points and measurement points. The chosen hardware for the validation is the PulsON 210 platform by Time Domain [42], which provides direct ranging measurements plus additional link information. For each measurement point, 500 ranging estimations have been performed towards each anchor, for a total of $(30 \times 4 \times 500) = 60.000$ measurements.

For explanatory purposes, detailed result for links involving anchor A2 are described in Table. I, being:

- A_i the Anchor Identifier ($i \in [1, 4]$);

[1] http://www.ismb.it

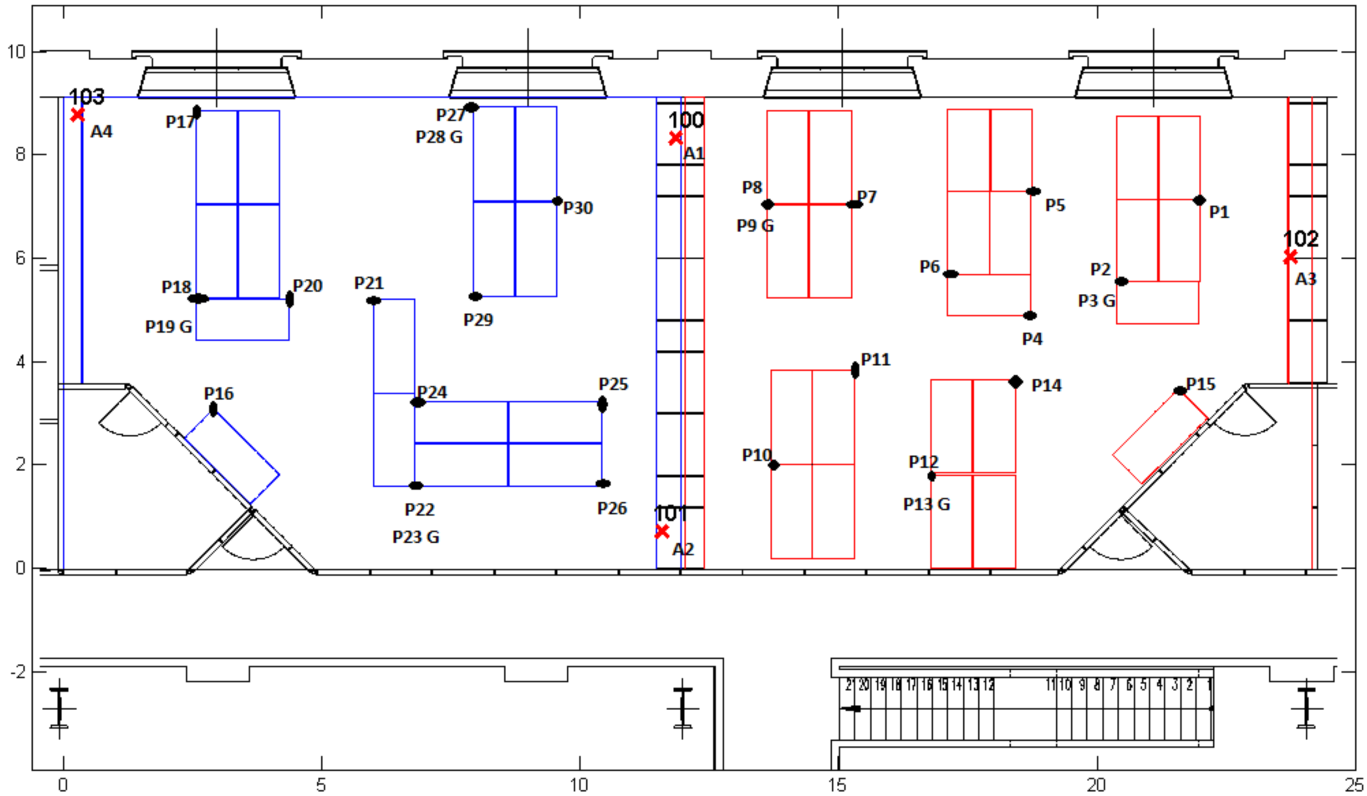

Fig. 8. Location of Measurement Points (P) and Anchors (A) for the experimental evaluation

- P_j the Measurement Point Identifier ($j \in [1, 30]$);
- $d_e(i, j)$ is the euclidean distance between A_i and P_j measured experimentally (in meters);
- $d_t(i, j)$ is the euclidean distance between A_i and P_j estimated by the tool (in meters);
- $\delta(i, j)$ is the relative error made by the tool in evaluating the link between A_i and P_j (in %) calculated as $\delta(i, j) = 100 \times \|d_t(i, j) - d_e(i, j)\|/d_e(i, j)$;
- $\epsilon_e(i, j)$ is the precision for the link between A_i and P_j measured experimentally (in meters), calculated combining the average error reported by the hardware and the standard deviation among the 500 measurements;
- $\epsilon_t(i, j)$ is the expected precision for the link between A_i and P_j estimated by the tool (in meters);

Table. II aggregates the overall performance evaluated during the experimental campaign for the four anchors, being:

- $\Delta(i, j)$ is the absolute error made by the tool in evaluating the link between A_i and P_j (in meters) calculated as $\Delta(i, j) = \|d_t(i, j) - d_e(i, j)\|$;
- $\Delta_{avg}(i)$ the average absolute error made by the tool for the links stemming from A_i (in meters) calculated as $\Delta_{avg}(i) = \frac{1}{30} \times \sum_{j=1}^{30} \Delta(i, j)$;
- $\delta_{avg}(i)$ the average relative error made by the tool for the links stemming from A_i (in percentage) calculated as $\delta_{avg}(i) = \frac{1}{30} \times \sum_{j=1}^{30} \Delta(i, j)/d_e(i, j)$;
- $E(\epsilon_t(i))$ the average relative error for the links stemming from A_i (in percentage) estimated by the tool.

TABLE I
A2 RADIO LINKS DETAILS

j	$d_e(2, j)$	$d_t(2, j)$	$\delta(2, j)$ (%)	$\epsilon_e(2, j)$	$\epsilon_t(2, j)$
1	12.53	12.53	0.04 %	0.05	0.33
2	10.31	10.06	2.39 %	0.05	0.26
3	10.28	10.06	2.20 %	0.06	0.26
4	8.32	8.29	0.30 %	0.14	0.22
5	9.89	9.72	1.75 %	0.18	0.26
6	7.75	7.47	3.69 %	0.05	0.33
7	7.58	7.33	3.20 %	0.05	0.26
8	6.71	6.68	0.41 %	0.59	0.18
9	6.98	6.80	2.53 %	0.28	0.24
10	3.36	3.44	2.36 %	0.05	0.09
11	4.99	4.90	1.98 %	0.06	0.13
12	5.54	5.37	2.99 %	0.05	0.19
13	5.86	5.52	5.64 %	0.19	0.29
14	7.41	7.47	0.91 %	0.14	0.20
15	10.46	10.38	0.71 %	0.13	0.27
16	9.05	9.02	0.37 %	0.05	0.16
17	12.02	12.18	1.33 %	0.13	0.21
18	10.12	10.10	0.16 %	0.05	0.18
19	10.16	10.19	0.22 %	0.17	0.36
20	8.57	8.54	0.34 %	0.05	0.15
21	7.20	7.20	0.00 %	0.05	0.13
22	5.02	4.90	2.28 %	0.14	0.13
23	5.10	5.07	0.63 %	0.05	0.09
24	5.43	5.44	0.25 %	0.05	0.10
25	2.92	2.85	2.41 %	0.04	0.07
26	1.63	1.60	2.00 %	0.05	0.04
27	9.00	9.02	0.16 %	0.04	0.16
28	9.70	9.11	6.07 %	0.58	0.48
29	5.93	5.89	0.52 %	0.05	0.10
30	6.72	6.72	0.01 %	0.06	0.12

TABLE II
OVERALL RESULTS

i	$\Delta_{avg}(i)$	$\delta_{avg}(i)$	$E(\epsilon_t(i))$
1	0.08	1.25 %	2.74 %
2	0.11	1.60 %	2.68 %
3	0.10	1.25 %	2.63 %
4	0.08	0.63 %	2.25 %
TOTAL	0.09	1.18 %	2.57 %

It can be observed that, while the tool in general over-estimates the expected ranging errors (ranging 2.5% to 3%), it correctly estimates ranging behavior of nodes in the scenario under test, providing precisions compatible with the technology.

The time required to perform the overall computation of the described scenario is in the order of $\tilde{3}0$ seconds on a normal work station (Intel Core i7, 4GB of RAM). ~~This is because of the non-optimal exhaustive approach chosen in the proof-of-concept setup.~~

VI. Conclusions and Future Works

In this paper we proposed a methodology leveraging convergence between BIM and WSN development support tools to support the planning of a WSN solution in a building. The methodology has been demonstrated through a simple use-case i.e. the evaluation of the ranging behavior of a WSN based on Ultra Wide Band (UWB) technology used for indoor positioning comparing predicted performance with results of a small-scale experimental evaluation.

The final result is that geometry and material information available in BIM can effectively benefit IoT-related tasks in the planning and commissioning phases, if proper interoperability between BIM and WSN development tools is achieved.

Overall, the described experience has shown that a number of key aspects must be taken into account to make the proposed methodology more effective in operating environments. Firstly, while significant work is being done to ensure that more standardized approaches are enforced in the BIM design community, it is important that building-related information exposed by the BIM-AL are sufficiently descriptive, yet simple enough to ensure that efforts required to re-use the existing model is significantly lower than the effort required to reproduce the model in an application-specific format. Secondly, in order to properly support evaluation scenarios set in complex buildings made of a large number of parts, the proposed tool should be re-factored to provide estimations without exhaustively exploring all building elements for each WSN node tuple. This is a key aspect to allow the use of the proposed methodology in optimization tasks, where the same scenario must be evaluated a very large number of times with slightly different conditions to find optimal solutions. Finally, in order to achieve more realism, more sophisticated radio models should be considered, coping more realistically with the details of the 3D geometry of walls and solid elements as well as with the radio properties of building materials.

Future works will focus on: the analysis and generalization of the open APIs exposed by the BIM-AL to ensure better compliance of the exposed information with BIM standards; the improvement of the current tool to support the evaluation of more complex, computationally-intensive scenarios; the adoption of more sophisticated and realistic radio models within the 3D Connectivity Engine; the extension of the proposed approach to support more complex planning tasks such as topology optimization.

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