

Patient-Device Association and Disassociation with a Real-Time Location System

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Abstract

In hospitals and clinics, medical devices incorrectly assigned to patients may cause various patient safety problems. Moreover, the unknown location of required mobile devices (intravenous pumps, cardiac monitors, etc.) represents additional issues for health providers such as unnecessary search effort, delays, and equipment underuse. To mitigate such issues, a patient-device connectivity management system that monitors and tracks patients and their assigned devices becomes an interesting option. Popular approaches for managing associations between patients and devices often involve barcoding systems, which still require scanning time, are prone to errors, and do not solve equipment location issues.

This thesis introduces a new system that exploits Real-Time Location System (RTLS) technology to track patients and devices and support simpler association by a nurse, until disassociation (voluntary or not) happens, at which point the nurse is notified. This system, called *Real-time Patient-Device Association and Disassociation* (RPDAD), interacts with nurses through their mobile device (tablet or phone). The system provides a new server-based application that interacts with an existing RTLS (hence enabling the reuse of current hospital infrastructure for mobile equipment tracking), a new Android mobile application for nurses, and a novel approach for automated disassociation tracking. The system was validated through proof-of-concept deployments in a university laboratory and in teaching hospital in Ontario, as well as with extensive testing for several configurations in a university laboratory. This thesis discusses the feasibility of the approach, its originality compared to the state of the art, and current technological limitations. We expect this system to help avoid usability and disassociation issues while increasing patient care quality and efficiency.

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List of Acronyms

Acronym	Definition
AR	Action Research methodology
API	Application Programming Interface
BCMA	Bar-Code Medication Administration
CEP	Complex Event Processing
DSR	Design Science Research methodology
EBSE	Evidence-based Software Engineering
ERC	Ekahau RTLS Controller
GPS	Global Positioning System
HF	High Frequency
HPBM	Health Provider-Based Mobile (application)
ID	Identifier
IV	Intravenous
JDBC	Java Database Connectivity
MAC	Medium Access Control
MSKCC	Memorial Sloan-Kettering Cancer Center
P2D	Patient-to-Device (or simply Patient-Device)
PBM	Patient-Based Mobile (application)
PCMCIA	Personal Computer Memory Card International Association
PPID	Positive Patient Identification
RFID	Radio Frequency Identification
RPDAD	Real-time Patient-Device Association and Disassociation
RTLS	Real-Time Location System
SSM	Soft System Methodology
TOH	The Ottawa Hospital
UHF	Ultra High Frequency
Wi-Fi	Wireless local area network
WSN	Wireless Sensor Network

Chapter 1. Introduction

Despite recent technological improvements in healthcare systems, hospitals still need to be provided with new and relevant technologies to improve patient care quality. This thesis defines and validates a novel approach that exploits a *Real-Time Location System* (RTLS) to associate and disassociate automatically mobile healthcare equipment with patients and responsible nurses. In this chapter, we discuss relevant motivations and provide the problem description. The research hypothesis and the methodology are also defined. At the end of the chapter, thesis contributions and the thesis outline are highlighted.

1.1. Motivation

An RTLS can identify and track the locations of assets, which are persons or devices. In this thesis, we support the possibility of tracking patients and their assigned medical equipment in real time, and of detecting when they are connecting or disconnecting. We use the terms *association* and *disassociation* to explain the transitions between existence and non-existence of connectivity between patients and devices. Patient-device association is important (especially with emerging mobile equipment that communicates patient status information to hospital information systems) to ensure that the right medication is provided to the right patient, that information about the right patient is transmitted to electronic health records, and that the right healthcare provider is alerted when a device is unexpectedly disconnected.

Currently, there are some issues regarding device-patient associations in hospitals. As patient safety is a primary objective for health providers, considering the accuracy of patient identification is essential, especially during the device association process. Manual association by healthcare providers (typically nurses) is one of the current methods of assigning the patient to the device according to their identifier (ID), which may increase the chances of errors, specifically for the incorrect re-association after an unex-

pected disassociation. Also, this method is time consuming; 35.3% nursing time is dedicated for documentation and 17.2% for medication administration, which is part of an association [28].

Another problem, which has motivated us to work on this important project, is linked to a common method of managing associations between patients and devices: the use of barcoding systems. Such approach is also time consuming and not always practical, despite relatively low percentages of errors reported by health providers. Bar codes can also be damaged or switched, they have low storage capacity, and they require a line of sight by the nurse to be used [15].

The third motivation for this research is the location of required mobile devices (intravenous pumps, cardiac monitors, etc.) often unknown by the care provider. Tracking equipment is crucial in asset management and especially in a centralized distribution model. Yet, a recent study illustrates that next to 60% of mobile devices remain idle at any given time while nurses spend over 20 minutes per shift looking for mobile equipment [30]. With better real-time tracking, hospitals can often reduce the amount of equipment inventory, which consequently reduces maintenance and service costs. Also, smaller inventories will cost less to replace as equipment ages. All the above issues represent the main motivations of this research.

1.2. Problem Description

Despite the reported benefits of barcoding systems, such as decreasing documentation, decreasing the number of medication error reports, and quick access to deliver appropriate dose at the right time, there is lack of accuracy that causes many problems. Incorrect labeling, damaged barcodes, scanner malfunctions and other issues prevent this method from being established at large¹. For instance, a nurse may fail to scan the patient or/and the medication, the barcode on the patient/medication may be unreadable to the scanner, or the wristband on a patient may be found on another patient or may be lost. Also, bar-

¹ See http://www.personal.psu.edu/vlg118/blogs/vicki_gutenkunst/Barcoding_file.pdf

codes have to be scanned one by one, and searching for the patient data on the system usually results in an increase in workload.

Moreover, the effectiveness of barcoding technologies in patient safety is limited in terms of using them consistently at the bedside. In a study of 85 Hospital Corporation of America facilities using Bar-Code Medication Administration (BCMA) in June 2004, only 64% of the patient armbands were scanned and only 86% of the medication labels were scanned [15]. BCMA is a difficult task, especially where it should follow the so-called *five rights*: right patient, right medication, right dose, right time, and right route of administration [51]. In addition, barcoding systems cannot determine that a device was disassociated unexpectedly from a patient.

For all of these reasons, the barcode-assisted patient-device association for higher acuity environments may not be the best solution and it certainly does not promote a positive workflow. Hence, a better approach to managing this association of wireless devices and intravenous (IV) pumps should be to design the right workflows [11].

The process of associating the correct device, which may have medication, to the correct patient is a major concern for health systems. The reliable identification of the patient and the device, and even of the associated nurse (as the nurse is legally responsible for the patient), is part of the solution. To put it another way, assigning identification tags to all members of an association process brings the possibility of an accurate identification. The use of RFID (Radio Frequency Identification) tags not only enables efficient and accurate *identification* for patients and devices, but also the tracking of the *location* of equipment and people, which is helpful for all health providers. As a result, studying solutions in that space might be beneficial.

1.3. Methodology

According to the definition of research methodology, which is the theoretical analysis of the body of methods and principles associated with a branch of knowledge [31], we consider our field of study to be software systems engineering. There are three common types of methodology that may support this research:

- The *Design Science Research* (DSR) methodology is rooted in engineering, and the purpose of design here is “to change existing situations into preferred ones” [24]. There are two variants here: episodic DSR and iterative DSR.
- The *Action Research* (AR) methodology could be another way to do scientific research here. Organizational action to create change for new knowledge in a clinical mode is its aim, as opposed to DSR’s aim which is creating an artifact to discover new knowledge in a generative (or creative) mode [6].
- The third option is *Soft System Methodology* (SSM), which is used less often for research methodology and more often as a systems development methodology. This approach lies between action research and systems science. It also includes system thinking and an iterative approach to develop a system (e.g., prototyping) [6].

Table 1 shows the similarities and differences of these research methodologies, and can help us choose the best one or a particular combination.

Table 1 Comparison of Characteristics of DSR, AR, and SSM [6]

Characteristics	DSR	AR	SSM
Orientation /Method for...	Research	Practice and Research	Practice
Goal	Problem Solving	Problem Solving and/or Behavioural Understanding	Problem Solving
Specificity	General	Situation Specific and General	Situation Specific
Design Role	Invention / Generative	Application or (Invention and Application)	Application or (Invention and Application)
Outcome	Design Theory or Artifact Shown to Have Utility	Situated Organizational Improvement (Behavioural Theory or Design Theory)	Situated Organizational Improvement

The third option is closely related to the challenges and work in this research. As Table 1 shows, SSM can be reliable in a systematic environment. However, this methodology is not sufficient for theoretical analysis. Therefore, thinking about a combination or adapted

version of SSM would be helpful and could cover the requirements of common software systems engineering research.

Ultimately, the *Soft Design Science Research Methodology* (Soft DSR) [6], which combines all necessary aspects of SSM with DSR and AR, is a suitable methodology to be used here. Soft DSR develops new ways to improve human organizations, especially with consideration for social aspects, and follows the activities of design, development, instantiation, evaluation and evolution of a technological artifact. Fundamentally, the common design science research process (design, build-artifact, evaluation) is merged with the iterative Soft Systems Methodology. At the end, we can achieve a general solution to a class of problems shown to operate in one instance of that class of problems [6].

Soft DSR has seven iterative activities (Figure 1) and its cycle continues until the social and technical problems are resolved.

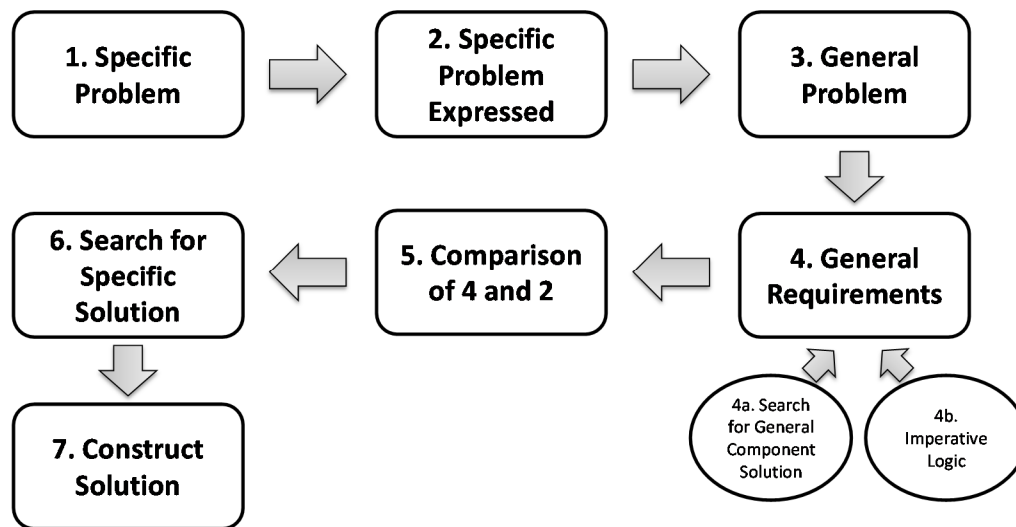


Figure 1. Soft Design Science Research [6]

- Step1.** Identifying a specific problem.
- Step2.** Transferring the specific problem to a specific set of requirements.
- Step3.** Translating the requirements into a general problem (a class of problems) in the design thinking world with both technical and social dimensions.
- Step4.** Designing a general solution (a class of solutions) for the general problem. This activity involves a combination of design science techniques, such as the search

for general components of the solution together with expressions using imperative logic.

- Step5.** Comparing constantly the general design requirements with the specific problem for fit. In this activity, the specific problem is re-articulated in terms of the general requirements and the imperative logic.
- Step6.** Searching for the specific components that will provide a workable instance of a solution to the general requirements and imperative logic.
- Step7.** Constructing an instance of the specific solution and deploying into the social system. In this way, the specific problem is changed (hopefully improved), learning is derived, and the cycle begins again [6].

We have followed the Soft DSR methodology with the following research steps:

1. **Identifying the problem:** We identified the problems of manual association and barcoding systems for patient-device associations.
2. **Identifying a specific set of requirements:** We need an accurate and reliable patient-device association system to address the problems caused by current systems.
3. **Identifying general problems:** Problems of current systems (reviewed in the literature survey) relate to the lack of automated association management capabilities, to unknown locations of many mobile devices, to the time spent managing associations, and to the absence of automated disassociation capabilities.
4. **Providing feasible requirements:** Transfer and translate general problems into general requirements to assess and adopt them by comparing the problems for a feasible system, which is here tracking patients and all assigned devices for association and disassociation, in real time, while taking advantage of emerging hospital infrastructures for location tracking.
5. **Comparing general requirements with specific requirements:** In this step, by comparing Step 4 with Step 2, we are trying to finalize our requirements. The resulting detailed goals and requirements are presented in this thesis (Chapter 4).

6. **Searching and finding a feasible system:** Evaluate and search the current systems for managing the association and the disassociation of a patient and a device (Chapter 3).
7. **Designing and development:** Develop a real-time location-aware system (Chapter 4), build a prototype and demonstrate it within a real hospital environment, and supplement this by validation experiments (Chapter 5).

1.4. Research Hypothesis

The research hypothesis is the following: *The design of a software system that **monitors and tracks patients and their assigned devices and manages their connectivity in real time** is feasible in a way that provides **accurate location** in order to **support patient safety**.*

The research hypothesis focuses on the possibility of having a real-time, location-based patient-device association and disassociation system that can provide accurate location of necessary objects to manage and track patients with their associated devices in a timely way. The main goal of this thesis is to provide a feasible solution to cover all highlighted points in the hypothesis.

1.5. Thesis Contributions

The main contribution of this thesis is the design of a real-time tracking system for patient and device association and disassociation. This system is named *Real-time Patient-Device Association and Disassociation* (RPDAD). By using RTLS technology, controlling and monitoring an association between a patient, (mobile) medical equipment, and provider (nurse) becomes feasible. Additionally, detecting disconnections (disassociations) between the patient and the device and notifying the relevant nurse, which are not covered in the literature, become feasible. A prototype developed for a major hospital in Ontario and scenarios that can happen in this environment are provided to demonstrate the importance of tracking associations and disassociations and to enable an evaluation in

terms of functionality and accuracy. The prototype also supports mobile access by nurses through a specifically-designed tablet/phone application².

1.6. Publications

This thesis led to two conference publications. The first one [54] is directly related to this thesis while the second one [7] is the topic of another thesis, but with shared application infrastructure (RTLS environment and database).

- **Rezaee, R.**, Baslymane, M., Amyot, D., Mouttham, A., Chreyh, R., Geiger, G. Location-Based Patient-Device Association and Disassociation. *4th Int. Conference on Current and Future Trends of Information and Communication Technologies in Healthcare (ICTH-2014)*, Halifax, Canada, September 2014. *Procedia Computer Science*, Elsevier, Vol. 37, 2014, pp. 282-286.
- Baslymane, M., **Rezaee, R.**, Amyot, D., Mouttham, A., Chreyh, R., Geiger, G. Towards an RTLS-based Hand Hygiene Notification System. *4th Int. Conference on Current and Future Trends of Information and Communication Technologies in Healthcare (ICTH-2014)*, Halifax, Canada, September 2014. *Procedia Computer Science*, Elsevier, Vol. 37, 2014, pp. 261-265.

1.7. Thesis Outline

The chapters of this thesis are as follow:

- Chapter 2: Defines basic relevant concepts and presents background information.
- Chapter 3: Provides a literature review covering existing patient-device association systems and mobile/tablet access to such systems by nurses.
- Chapter 4: Presents the RPDAD system requirements, architecture and design by considering the main challenges and possible usage scenarios.

² Disclaimer: Note that a first prototype of this application was developed as part of a graduate *directed studies* course on mobile application development, taken in the winter 2014. The version presented in this thesis is however much improved in terms of user interface, number of features, and overall robustness.

- Chapter 5: Discusses the implemented scenarios and provides results of the deployment and experimentation phases.
- Chapter 6: Evaluates the validity of the system by comparing its features with features of currently available systems, and discusses threats to the validity of this work.
- Chapter 7: Concludes the overall thesis and presents future work items.

Chapter 2. Background

This chapter presents basic concepts related to patient-device association/disassociation and to RTLSSs, with a particular focus on the Ekahau RTLS technology [16], used in this thesis.

2.1. Patient-Device Association and Disassociation

Typically, there is no standard term used for describing a link or connectivity between a patient and a medical device. When a caregiver, such as a nurse, starts assigning a medical device, such as an infusion pump that has an ordered dosage, to a patient, the nurse may write down the information in the patient record [29]. Generally, an *association* in this case means the *act* of associating or the *state* of being associated. Specifically, by receiving the identification of a patient and a device, and recording their association, a *patient-device* (also called *patient-to-device* – P2D) association happens [29]. P2D associations often involve intelligent devices with *connectivity*, where connectivity enables devices to transmit patient-related information to a hospital information system. *P2D association* is hence an industry term referring to the process of using Positive Patient Identification (PPID) to establish the association of one or more devices to the confirmed patient [11].

As briefly discussed in section 1.2, although several solutions and products exist, so far, there is no real way of managing patient-device associations efficiently. In this thesis, the patient-device association process is concerned with the automated recording of assigned or connected medical device(s), such as IV pumps and vital sign monitors, to a confirmed patient. Such process is triggered by a healthcare provider (typically a nurse) when next to the patient. Additionally, we assume that the patient, the device and the provider have already been assigned a patient tag, an asset tag and a badge (respectively), which enable location tracking.

Similarly, a P2D *disassociation* represents the termination of an association between a patient, a device, and possibly the healthcare provider responsible for the association. A disassociation may be caused by a variety of reasons, such as being explicitly requested by a healthcare provider or by having a patient moving away (by mistake or on purpose) too far from the associated device [29]. To distinguish these two cases, the terms *manual disassociation* and *automatic disassociation* are used in this document. Detecting and reporting automatic disassociations is an also important contribution of this thesis.

2.2. Real-Time Location Systems

Real-time location systems (RTLS) are a form of local positioning system used to identify and track objects assigned with (RFID) tags, in real time. This is analogous to a Global Positioning System (GPS), but an RTLS does not use satellites nor does it offer global coverage; coverage is usually limited to a specific building. RFID tags can operate in one of two modes: active or passive. Their main difference lies in how power is supplied: in the passive mode, no power source is required (but proximity is required), whereas in the active mode, batteries (and re-charging) become necessary [9].

Many RTLS are implemented with wireless passive or active tags attached to devices or people and used for sending (and sometimes receiving) signals. Such signals include location information, or a signal that will trigger a flashing light, an audio signal, a vibration buzzer, or a text message. For transferring information, tags need to communicate with a location software system (RTLS controlling system) which logs, stores, detects and assesses the information. In fact, real-time location systems are often used when location of tracked resources change and need to be updated [9].

In the past few years, real-time location systems have started being used by healthcare organizations. Hospital RTLS are designed to identify personnel, or patients, or medical devices, which are all equipped with tags (some of which supporting being washed and/or disinfected). Tracking mobile equipment with an RTLS allows hospitals to better manage their inventory, find equipment quickly, avoid losing equipment, and eventually reduce equipment acquisitions or rentals [19][57]. Tracking hospital personnel improves clinical processes, including assigning health providers to patients automat-

ically, and even disciplining clinicians or other staff who are underperforming in their roles (although this last aspect can raise privacy and ethical issues) [19]. Tracking patients helps avoid losing them as they are moved to various departments within a hospital (or if they attempt to leave unexpectedly, which is useful in mental health institutions), supports verifying their identities before medical procedures, and helps improving discharge processes to provide quicker turnover of beds [19]. Therefore, the benefits of implementing RTLS in healthcare can be characterized as increased efficiency and improved safety.

2.3. RTLS Components

Real-time location systems usually include many types of components, which are illustrated here with a specific technology from Ekahau. Ekahau is a company that has been providing RFID-over-Wi-Fi real-time location systems since 2000³. This means that the Ekahau RTLS work everywhere where Wi-Fi (802.11) networks are already available. The Ekahau RTLS solution is one of the most accurate RTLS solutions available on the market today. Figure 2 structures common Ekahau components in four layers. In this part, we focus on the Ekahau components used in our system.

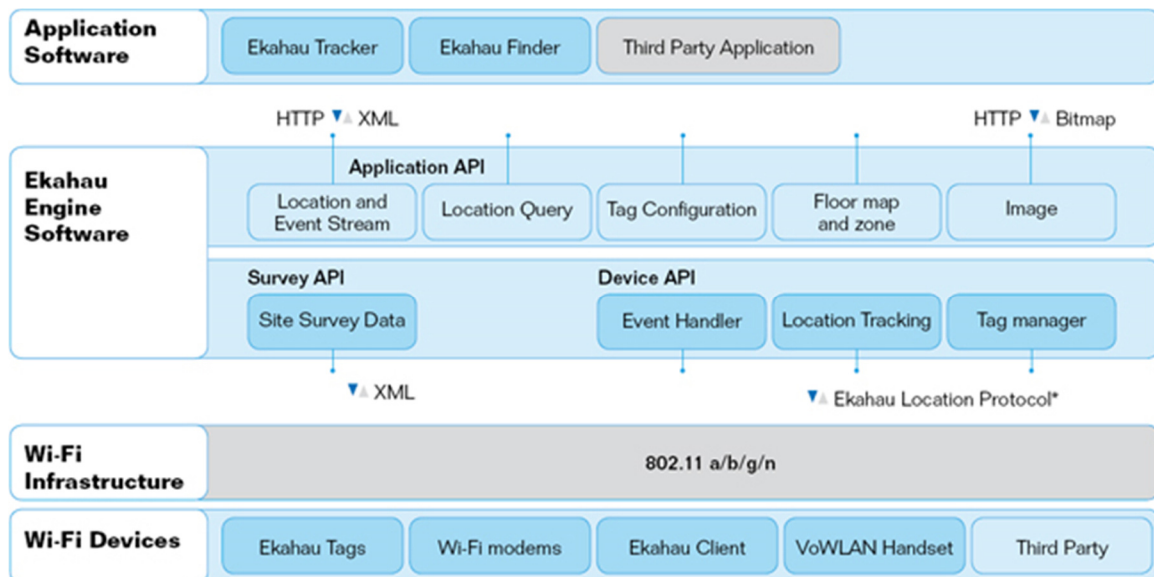


Figure 2. Commercial RTLS Architecture [17]

³ <http://www.ekahau.com/real-time-location-system/about-us>

2.3.1 RTLS Controller (ERC)

This component, part of the Ekahau Engine Software in Figure 2, is basically the brain of the RTLS. The ERC runs on a server as a service that receives all data from Ekahau tags. The ERC can estimate the location of tags by using a calibrated positioning model and several patented mathematical algorithms [17].

2.3.2 Site Survey

This component, also part of the Ekahau Engine Software in Figure 2, is a complete Wi-Fi planning and survey application for data gathering. This application is to upload maps and information about Wi-Fi signal strengths into the RTLS Controller in order to add “location awareness”. The site is surveyed by performing a walkthrough to record the strength and density of the WLAN’s signals. This information is then activated in the RTLS Controller and tracking becomes enabled [17].

2.3.3 Activator

This component is part of the Application Software layer in Figure 2. The Activator is an application that enables one to activate and configure tags (e.g., in terms of how often they should send location updates). In the ERC, management, configuration and grouping of tags require them to be activated [17].

2.3.4 Wi-Fi Tags

Ekahau tags are shown in the Wi-Fi Devices layer of Figure 2. They work like small computers that transfer information over the Wi-Fi network to the ERC. The ERC uses this information to determine tag location [17]. There are several types of Ekahau Wi-Fi tags (with different capabilities and energy consumption characteristics) that we use in our system (Figure 3): T301A (Asset tag, with low location refresh frequency but with batteries that can last many years), T301B (Badge Display tag, for healthcare staff, with many buttons and a small screen), and T301W (Wi-Fi tag for patients, which can be washed and disinfected). The last two types usually require being recharged daily. All of these tags also support infrared communication.



Figure 3. Ekahau Wi-Fi Tags

2.3.5 Location Beacon

A location beacon (Figure 4) is a battery-powered infrared transmitter [17], which is optionally used with tags to enhance location accuracy. Beacons require line of sight to communicate with tags. The beacons provide their identifications to the tags, which then communicate this information to the ERC. The beacons currently used in our system are Ekahau LB1, which are compatible with T301B, T301BD, T301W tags. Recently, Ekahau has launched a new version of their beacon, LB2, and enhanced the compatibility of beacons to adjust with any tags. The beacons can be configured to cover a full room, a zone of 2-3 square meters (e.g., for a patient bed), or a micro-zone of about half a square meter (for very high precision).



Figure 4. Ekahau Location Beacon

2.3.6 Vision Software

The Ekahau Vision software is similar to the Ekahau Tracker in the Application Software layer (Figure 2). This is a multi-user Web application used for a quick access to asset locations. Basically, this is an end-user application that monitors objects in a highly-visual way, where tags (and what they represent) can be displayed on a map (of the floor, room, etc.), in real time.

2.4. Chapter Summary

The chapter presented basic terms used in this research, including patient-device association and patient-device disassociation. Furthermore, basic concepts and background related to RTLS technology were covered. The commercial RTLS components, provided by Ekahau, which are relevant to this thesis were finally introduced. The next chapter delves into existing literature on real-time patient-device association monitoring, from the perspective of capabilities found on servers, but also from the perspective of mobile clients (e.g., on tablets) used by nurses.

Chapter 3. Literature Review

Using different point of views and looking at existing work is always beneficial, especially to avoid duplication. This chapter includes a semi-systematic literature review of research on related work by selecting high-quality articles or studies that are relevant and valid. It also categorizes and summarizes the selected approaches. The literature review is done in two parts:

- Server side, where the main capabilities reside. This part covers association management, location tracking, and real-time aspects.
- Client side, used to access the server functionalities through a mobile device (e.g., tablet or phone).

3.1. Methodology

As Kitchenham et al. have observed, software engineers in general, and empirical software researchers in particular, should consider evidence-based studies in their work and decisions [35]. This literature review is inspired from Kitchenham et al.'s framework: Evidence-based Software Engineering (EBSE). This review is not fully systematic according to EBSE's definition, but it is semi-systematic in the sense that it covers the main steps such as going through existing primary reports, reviewing them in-depth, and describing their results. The aim here is to find and classify the primary studies in our specific topic area [35]. The method used here is composed of six steps, shown in Figure 5, applicable to the two parts of the survey: the server side and the client side. In addition, comparison criteria are defined, which enables the comparison of existing techniques (and later of the RPDAD system), and the analysis of existing gaps in current approaches.

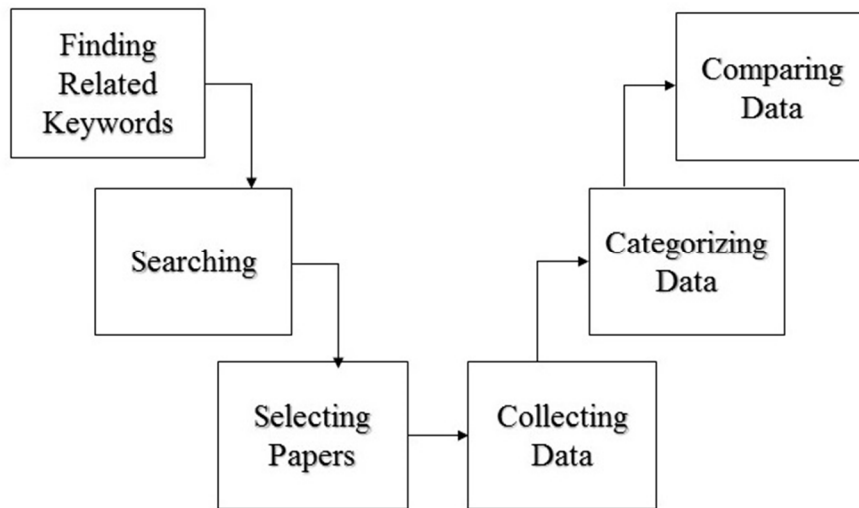


Figure 5. Systematic Literature Review Steps

3.2. Server Side (Main Capabilities)

3.2.1 Search Keywords

According to the research hypothesis, this research investigates real-time location systems in healthcare to support patient safety in terms of assigning the right medical device and of tracking patient-device associations in real-time to manage their connectivity and detect unexpected disassociations. In this context, the keywords used for querying search engines should support all criteria mentioned in the research hypothesis. The five criteria selected here are categorized in Table 2. Each column defines terms and synonyms for the criteria: real-time tracking, location base, patient safety, P2D association and disassociations. Therefore, some of the most important candidate keywords to be searched are those collected in Table 2.

Table 2 Research Keywords

Real-time tracking	Location base	Patient safety in healthcare	Association	Disassociation
real-time patient tracking	location base tracking	smart hospital room	RTLS-base device connectivity	medical device tracking
real-time locating application in hospitals	monitoring medical device location	system tracking for patient safety	medical device tracking	vital signs monitoring and patient tracking
health care real time locating solution	health care real-time locating solution	intelligent hospital	patient-device association	RFID asset monitoring system
RFID asset monitoring system	smart object in hospital	point-of-care systems	barcoding system in healthcare	patient device disassociation
medical device tracking		hospital information systems	patient tracking	unknown medical devices
patient identification system		hospital and RTLS	patient-device connectivity	mobile asset management
positive patient identification		hospital and RFID	patient-centered	mobile medical devices
monitoring system			medication administration	

3.2.2 Search Process

For these research options, common search engines, such as IEEE Xplorer, SpringerLink, ScienceDirect, ACM DL, and Google Scholar have been used. Also, the general Google search engine was used in some cases. For these engines, the advanced search option was selected and queries were composed by relating keywords with conjunctions (AND/OR). In general, an AND was used for choosing different categories (in Table 2) and an OR was used for synonyms in a same category. For example, for the server capabilities, some search queries performed include:

1. “association” AND “patient-centered” AND “medication administrator”.
2. “hospital information systems” AND “real-time” AND “mobile medical devices”.
3. “Patient identification system” AND “RTLS”.
4. “Real-time location” AND “health care”.
5. “Patient-device association” OR “Patient device connectivity”.
6. “Patient-device disassociation” OR “Unknown medical devices”.

Not all combinations were searched, only those that returned a reasonable number of results (not too few, not too many).

3.2.3 Study Selection

Using our queries and the selected search engines, 53 documents were selected (often one paper would be returned by many search engines). However, by considering their titles and abstracts, only 25 documents were related to our context. Eventually, by studying these papers more closely and by selecting a subset of 17 relevant papers based on their results and validity (Table 3), we were able to categorize existing work.

3.2.4 Data Collection

As Table 3 shows, concerns about patient tracking automation go back to the end of the 1980's [26].

Table 3 Selected Papers for RTLS Technologies

Year	Ref	Article Code	Article title	Search Engine
1989	[26]	P1	Person monitoring system	Google
2004	[49]	P2	Mobile Medical Device Connectivity: Real World Solutions	IEEE Xplore
2006	[25]	P3	Passive RFID Asset Monitoring System in Hospital Environments	IEEE Xplore
2006	[23]	P4	Vital Signs Monitoring and Patient Tracking Over a Wireless Network	IEEE Xplore
2007	[14]	P5	GeoHealth: A Location-based Service for Nomadic Home Healthcare Workers	ACM DL
2008	[20]	P6	Tracking the social dimensions of RFID systems in hospitals	ACM DL
2009	[21]	P7	Patient Centric Identification and Association	IEEE Xplore
2010	[46]	P8	Smart medical environment at the point of care: Auto-tracking clinical interventions at the bed side using RFID technology	ScienceDirect
2010	[43]	P9	Real-time location and inpatient care systems based on passive RFID	ScienceDirect
2010	[29]	P10	Patient to Device Association	Google
2011	[22]	P11	Impact of Smart Room Designs on Workflow	Google Scholar
2011	[27]	P12	Nurses' Visual Scanning Patterns during the Medication Administration Process	IEEE Xplore
2011	[60]	P13	Leveraging complex event processing for smart hospitals using RFID	ScienceDirect
2012	[19]	P14	Evaluation of real-time location systems in their hospital contexts	ScienceDirect
2013	[9]	P15	Location-Aware Business Process Management for Real-time Monitoring of a Cardiac Care Process	ACM DL
2013	[45]	P16	Automatic patient and device recognition and association system	Google Scholar
2013	[52]	P17	Integration of Active RFID and WSN for Real Time Low-Cost Data Monitoring of Patients in Hospitals	IEEE Xplore

Today's technologies, which target mobile asset/device tracking, often involve ultrasounds and radio frequency identification, either working over Wi-Fi or Wireless Sensor Networks (WSN) [52]. In the past few years, several hospitals started looking into automating patient-device association management.

In 2004, there was an attempt to track hundreds or even thousands of infusion pump devices with an integrated system that connects medical device data with a hospital information system [49]. In 2006, a technique that exploits passive RFID technology is applied to monitor Telemetry Transmitters to prevent losing them, since they are items often lost in hospitals [25]. Also, in 2006, a pre-hospital patient care system with algorithms to monitor patient vital signs and wearable sensors to sense and record vital signs into an electronic patient record have been designed to share real-time patient information [23]. In 2007, the GeoHealth system was designed to support activities, and alarms adapted to the users' location, for distributed and mobile collaboration [14]. In 2008, Fisher and Monahan evaluated the sociology effects of RFID technologies on hospitals in order to find a solution for standardizing RFID technology for e-health [20].

In 2009, the Memorial Sloan-Kettering Cancer Center (MSKCC) in New York started work on a patient-centric identification and association platform that represented a significant advance in the management of clinical patient information [21]. In 2010 at the Tokyo Medical and Dental University, a smart room with four beds was set up with a wireless network. Passive and active RFID tags were attached to patients, nurses, major medical equipment such as carts and an intravenous (IV) poles, as well as medications and small medical supplies. This configuration was studied to ensure patient safety by reducing misidentifications of patients, medical errors, and nurse workload [46]. Moreover, the same year, a solution for care and control of patients in a hospital based on passive high-frequency and ultra-high frequency RFID was provided [43]. This solution aimed to support offline work to increase application reliability under network failures. A patent [29] also provided a way to support associations and disassociations, but not in real time. Systems based on this patent can only identify patients and devices through barcoding (or by fetching them from a database) and then associate and disassociate them. In 2011, He et al. studied an approach for tracking objects in order to reduce errors and to improve healthcare delivery [27]. Basically, this approach focuses on nurse track-

ing during the medication administration process using visual scanning patterns. The same year, Yao et al. proposed a complex event processing (CEP) framework merged with an RFID technology for managing hospital data from a variety of sources, specifically for surgical procedures [60]. All patients, medical equipment and doctors are equipped with RFID tags and the hospital is equipped with RFID readers in different locations to communicate with tags. As a result, an RFID-enabled smart hospital can generate a variety of data streams that can be processed and correlated by the CEP engine [60]. In 2011 again, MSKCC in New York used a different configuration involving barcodes and RTLS as a smart environment that provided a robust infrastructure (with a combination of wired and wireless networks) for associating the right patient with the right medication and the right dosage [22].

In 2012, Fisher and Monahan provided another study suggesting that the current best use of RTLS is for asset tracking, but at the condition that the whole hospital be involved with the RTLS, to centralize control of the system [19]. Many other authors support the use of RTLS for asset tracking, using different technologies and strategies (e.g., Shirehjini et al. [57] use passive RFID tags on flooring plates [57]). In 2013, a new secure RFID smartcard model based on the ISO/EIC-14443 standard [32], which offers more storage capacity and higher processing power than previous RFID tags, was proposed to contain human information [52]. Also, a patent was issued in 2013 that describes the use of an association mechanism based on image processing (images of patients and devices), but which is still costly [45]. The integration of active RFID and WSN is another possibility to monitor body sensors connected to patients [22]. However, again, these solutions incur costs additional to those already invested in RTLS-based mobile asset management. Also, none of these approaches handles automatic disassociations.

The system proposed in this thesis makes use of existing asset management infrastructure based on an RTLS and RFID tags (from EkaHau in our prototype [16]) not only to track mobile assets, or track healthcare providers and patients (as in care flow management scenarios [9]), but also to provide the hospital with an automated, interactive system for patient-device association/disassociation that aims to eliminate the steps that cause errors and delays.

3.2.5 Data Categorization

This section categorizes, in Table 4, the 17 papers from Table 3 according to common important concepts (mostly derived from our keywords and needs), to illustrate their similarities and differences. The most important categories for analysis are:

- The type of *technology* used.
- The type of *tracked objects* (patient, device, provider, etc.), leading to the objective of tracking.
- Whether *association* and *disassociation* management is covered.
- Whether *real-time* communication is supported.
- The *effectiveness* of the work/output.
- The availability of an *implementation* (or equivalent form of experimentation).

The most important functionalities, and most effective factors in the comparison part, are the support for P2D association and disassociation activities. Although all related approaches have object tracking responsibilities, the P2D association and disassociation factors are essential for the evaluation.

Table 4 Related Work

Article	Country	Hospital	Technology	Track	Asso. Coverage	Disasso. Coverage	Real time	Effective	Implem.
P1	USA	Not specific	Scanner, Radio Signal/ Receiver	Patient	No	No	Yes	Yes	Yes
P2	USA, CA	None	wired, wireless, hybrid systems	Device	No	No	Yes	Partially	No

Article	Country	Hospital	Technology	Track	Asso. Coverage	Disasso. Coverage	Real time	Effective	Implem.
P3	USA, CT	Hartford Hospital	Passive RFID	Device	No	No	No	Yes	Yes
P4	USA, DC	Suburban Hospital, Johns Hopkins Paediatric Trauma Centre, and an auxiliary centre.	Wearable Sensors ⁴ , Pre-hospital Software, Vital Sign Monitor Algorithm	Patient, Provider	No	No	Yes	Yes	Yes
P5	Denmark	Not specific	Google Maps, GPS, Web 2.0	Location-base (people, devices)	No	No	Yes	Yes	Yes
P7	USA	MSKCC	RFID	All	Yes	No	Yes	Yes	Unclear
P8	Japan	Medical & Dental University	PRFID ARFID	Patient Nurse Device Supply	Yes	No	Yes	Yes	Yes
P9	Spain	Not specific	Passive RFID	Patient Device	No	No	Yes	Yes	Partial
P10	USA	Not specific	Barcoding Database	No Tracking	Yes	Partial	No	Yes	Patent
P11	USA, NY	Memorial Sloan-Kettering Cancer Center MSKCC	ARFID, PRFID, Barcode, HFWD	Patient Staff Device Supply	Yes (Smart-room/Alert)	No	Yes	Yes	Yes
P12	USA, Virginia	Not specific	Eye tracking devices ⁵	Nurse	Partial	No	No	Yes	Unclear
P13	USA	Not specific	RFID CEP	Hospital Workflow (surgical workflow)	No	No	Yes	Yes (especially in surgery)	Prototype
P15	Canada	Osler Hospital	RFID BPM	Patients Physicians Nurses....	No	No	Yes	Yes	Yes
P16	USA	Not specific	Image Processing	No Tracking	Yes	No	No	Costly	Patent
P17	India	Not specific	RFID WSN	Patient	No	No	Yes	Yes	Case study, 2 Patients

⁴ The wearable sensors provide four functionalities: vital signs monitoring, location tracking, medical record storage, and triage status tracking [23]

⁵ By finding links between whether nurses identifies a patient identification error while administering a medication and their two fixation scan-paths [27].

3.2.6 Data Comparison and Analysis

As shown in Table 3, the oldest concerns about patient tracking go back to 1988. This shows that patient tracking has been a major challenge for health systems for a long time. There are many reasons for this situation, such as improving patient security by minimizing the number of lost patients, and improving patient safety by assuring the right medication process. This concern has grown more and more, even in the presence of much progress in technology.

For those cases in Table 4 that do not have the association and the disassociation responsibility, it should be mentioned they do monitor patients, devices or staff, but just for security reasons (lost assets, lost patients, etc.) or they monitor that the right medication has been controlled. Still, there are four cases closer to our work: P7, P8, P10 and P11. First, in articles P7 and P11, which have the same authors and research topics but over two different years, the authors have used a mix of technologies to create a smart health environment and track all kinds of objects. Despite such smart environment, disassociation functionalities were ignored. Second, in article P8, the same scenario is repeated, but just using RFID technology, with a system implemented in a real health environment in Japan. Third, in article P10, there is no capability defined to track objects, and RFID or RTLS technologies are not involved, but a patient-device association feature is involved, and manual disassociation can be handled. In a nutshell, all reviewed approaches (except article P10) have a common objective, which is about tracking patients, devices or providers, and most of them have used RFID in real time. However, associations are seldom involved, and automated solutions for disassociation are ignored. Therefore a closer study of RTLS could potentially bring many benefits to hospitals in term of improving patient-device association management. In section 6.1, these related approaches will be compared precisely with our RPDAD system.

3.3. Client Side (Mobile Access)

As mobile applications are becoming widespread for many usages in industry, especially in healthcare, it is important to understand the existing and potential roles that such applications can play for enabling nurses to interact with an association management server.

This section provides an assessment of some available mobile applications in healthcare according to their usability areas. Furthermore, real-time characteristics of these applications, which represent another important area in this thesis, are considered.

3.3.1 Search Keywords

The search criteria have been defined with two attributes in mind: usability in healthcare, and real-time capabilities. In this context, the important keywords investigated included: "Mobile application and patient tracking", "Real-time patient tracking by mobile application", "Patient tracking mobile app", "Patient Tracker", "Mobile application in healthcare", "Mobile nursing", "Mobile patient care", and "Android applications and hospitals".

3.3.2 Search Process

Several search engines, namely IEEE Xplorer, ScienceDirect, ACM DL, and Google Scholar, have been used. Also, the general Google search engine was used in some cases, especially when some commercial applications were found.

3.3.3 Study Selection

For this literature review on mobile clients, 47 publications (papers, journals, reports, websites, etc.) were collected. After inspecting the papers, many did not cover both conditions (healthcare usability and real-time capabilities) and were filtered out. 10 publications were completely commercial, and Table 5 summarizes some relevant ones and illustrates their diversity. In the end, 15 papers were selected for evaluation.

3.3.4 Data Collection

After collecting 15 relevant related publications (see Table 6), according to their functionality, the papers were divided into two categories: patient-based mobile (PBM) applications and health provider-based mobile (HPBM) applications. Table 7 shows some important prototyped or developed applications in the healthcare field.

Table 5 Some Mobile Applications on the Market

Application	Market
OASIS-C Patient Tracking Mobile App	(By Oasis) This mobile application can easily keep track of patient records and their basic information. Concisely interpreted to a simple form, it also enables the user to input only the information necessary and required by the medical facility.
Patient Tracker App	This application is available for iPad and Android tablets. It can help nurses and doctors check and track patients' general information, medicines, and vital signs.
Mobile Apps from Mayo Clinic	(Patient-based) This application offers health news and information from the Mayo Clinic, online appointments, help for navigating the Mayo Clinic, secure access to personal health information, and local information about Mayo Clinic locations in Arizona, Florida and Minnesota.
Cardio Net MCOT App	CardioNet provides the next-generation ambulatory cardiac monitoring service with beat-to-beat, real-time analysis, automatic arrhythmia detection and wireless ECG transmission. Moreover, this application offers physicians simplified access to their patient data with instant on-line access to the suite of cardiac monitoring reports.
Midwife Patient Tracker (beta)	This application tracks Midwifery Patients and calculates due dates, weeks of gestation and postpartum.

Table 6 Mobile Applications: Selected Papers

Reference/ Year	Article Code	Article title	Description
[41] 2008	PBM1	Personalizing the Self-Care Process for Patients	Remote monitoring of a patient's vital measurements.
[12] 2009	PBM2	Mobile-Phone Based Patient Compliance	Capable of self-monitoring and self-regulation with real-time reporting to the provider and rapid feedback to the patient
[53] 2010	PBM3	Application of Virtual Mobile Networking to Real-Time Patient Monitoring	Physicians are able to monitor the vital signs of patients remotely through the patient's smart phone (WBSN).
[18] 2011	PBM4	Mobile Feedback System	For Integrated E-health Platforms to improve Self-Care and to support communication between Doctor and Patient instead of substituting it.
[2] 2012	PBM5	Sleep Apnea Monitoring using mobile phones	Provides doctors and sleep specialists with remote access to patient records and allows them to confirm their initial diagnosis.
[56] 2013	PBM6	A Mobile Health Application for Outpatients Medication Management	Allows users to register medications through the mobile phone camera to capture the barcode available on medication boxes.
[58] 2013	PBM7	Android Application Developed to Extend Health Monitoring Device Range and Real-time Patient Tracking	Monitors people at risk in real time even if they are outside of their home and the wireless home gateway is out of range.

Reference/ Year	Article Code	Article title	Description
[13] 2006	HPBM 1	A hybrid mobile-based patient location tracking system for personal healthcare applications	Assists caregivers or family members in locating patients such as elderly or dependents when required, especially in emergencies.
[39] 2007	HPBM 2	A Mobile Care System With Alert Mechanism	Physiological signal recognition algorithms that were implemented in mobile phones without affecting their original communication functions.
[59] 2008	HPBM 3	Monitoring Behavioral Patterns in Hospitals through Activity-Aware Computing	Monitors patients' behavioral patterns and notifies nurses of relevant patient states through a bracelet wore by nurses.
[38] 2008	HPBM 4	Multipurpose mobile Platform for telemedicine applications:	Can be used in a number of telemedicine and wellness applications to provide connectivity between healthcare professionals, patients and measurement devices.
[37] 2012	HPBM 5	An Android-Enabled Mobile Framework for Ubiquitous Access to Cloud Emergency Medical Services	Makes Emergency Medical Services accessible by Android-enabled mobile devices and incorporates a customized asynchronous notification feature whereby caregivers are notified of critical data updates in a way that efficient utilization of mobile device resources is achieved.
[50] 2013	HPBM 6	A Virtual Real-time Multimedia Service Framework on Handhelds to enable Remote Real-time Patient Monitoring for Mobile Doctors	Supports continuous access to the online patient vital medical data, and monitors the physical condition of the patient through video streaming.
[55] 2013	HPBM 7	A mobile application for ambulatory electrocardiographic monitoring in clinical and domestic environments	Runs under two scenarios: patient and doctor mode, allowing medical personnel to define different configurations. Both modes permit users to visualize in real time captured readings and tracings.

In PBM articles, generally the mobile application is activated by a patient that should be tracked in real time [18], and a controller system manages the patient's movements, behaviors, medicine, vital sign measurements, etc. Else, a patient and a doctor can work together and activate the application to have the patient tracked in real time [53]. So far, in terms of usage, there are no similarities with our RPDAD mobile application, which is activated by a nurse (health provider), but in terms of real-time functionality, there can be some common points. On the other side, HPBM articles can be similar in terms of the application activation. By considering the real-time technology used in each approach, a

health provider can manage the patient’s activities, or medicines, or physical conditions [55].

3.3.5 Data Categorization

Two tables are provided to summarize of these related works in terms of their healthcare areas and real-time technologies. In this section, supporting P2D association and disassociation features is not a major concern, although the main activities in this thesis’ mobile application relate to these two features. Table 7 identifies all collected patient-based mobile (PBM) applications by specifying their patient care area, the application platform, and the technology used for real-time capabilities. Table 8 does the same but for the health provider-based mobile (HPBM) applications.

Table 7 Patient-based Mobile Applications

Code	Patient Care Coverage	Platform	Real-time Technology
PBM1	Diabetes and Cardiovascular Diseases	Any mobile phone	Connecting to devices via Bluetooth and to the Web server via GPRS
PBM2	Chronic diseases	Any mobile phone	Wireless medical sensors and Bluetooth Wi-Fi and GSM-based localization
PBM3	General	Android mobile phones	1. Wireless sensors (802.11), ZigBee or Bluetooth for connectivity to the mobile phone. 2. TCP/UDP
PBM4	Diabetes	Any smart mobile phone and medical doctor’s PC	Not real-time, but by using web services
PBM5	Sleeping disorder	Any smart phone	Phone: GPRS, Wi-Fi/3G
PBM6	Medication	Android OS	Not real-time, but by using web services
PBM7	General	Android mobile phones	Bluetooth for device connectivity and GPS for patient tracking

Table 8 specifies another factor, which is the activator, to make it clearer who is responsible for the application activation, i.e., a nurse or a physician.

Table 8 Health Provider-based Mobile Applications

Code	Patient care coverage	Platform	Real-time technology	Activator
HPBM1	General	Any mobile phone	Cell-ID, GPS, MIS server, SMS (Alerts)	Nurses
HPBM2	Hypertension and arrhythmia (blood pressure and pulse monitor)	Any mobile phone	Mobile-care device GSM/GPRS, Bluetooth	Nurses, Patients, Physicians
HPBM3	General	Any mobile phone	Wireless networks, PDAs, RFID tags for patient tracking voice-activated communication devices and sensors for patient monitoring	Nurses
HPBM4	General	Any mobile phone	Java Bluetooth API (JSR 82) 3G/GPRS	Healthcare Professionals
HPBM5	Emergency Department	Android OS	Google Cloud Messaging Web services (Wi-Fi)	Healthcare Professionals
HPBM6	Vital sign Monitor assigned to the patient	Any smart phone	IP Camera Signaling TCP Connection RFB protocol Signaling (Wi-Fi/3G)	Physicians
HPBM7	Cardiology	Android and iOS	Bluetooth 4.0 interface for Apple devices Web (internet / remote servers)	Physicians, Patients

3.3.6 Data Comparison and Analysis

As shown in Table 7, in each suggested application, a mobile phone is part of the devices assigned to the patients that should be carried to help the tracking system function properly. PBM3 and PBM7 (highlighted in the table) are somewhat similar and interesting in terms of patient tracking, especially since PBM3 uses TCP/UDP technology for communicating with the controller.

In Table 8, in each case, there are several helpful technologies for establishing communication between an existing server and the provider's mobile phone. It is worth noting that HPBM1 is able to track patients in real-time and that HPBM5 is able to notify nurses of critical data updates from the patient side. HPBM6 supports continuous access to the online patient vital medical data, and monitors the physical condition of the patient through video streaming. Another important point is that all mentioned applica-

tions do not support tracking patients and devices simultaneously. However, in general, all reviewed approaches have some common objectives, which are to help the tracking system function properly and to simplify the steps of patient care processes, especially for health providers.

3.4. Chapter Summary

We have reviewed many existing works that use RTLS-based patient care systems to understand the efforts invested in improving performance and quality of care. We also have observed how RTLSs can be beneficial for hospitals. Also, the characteristics of some healthcare mobile applications have been evaluated to check their patient tracking capabilities in real time.

In the next chapter, we introduce the RPDAD system, with an emphasis on its architecture, design and implementation.

Chapter 4. System Architecture, Design and Implementation

This chapter presents and discusses relevant issues and project goals, requirements for association and disassociation management, and RPDAD scenarios and architecture, including high- and low-level designs.

4.1. System Goals

As discussed in the problem description and in the literature review, there are many issues to be considered for patient-to-device processes, such as:

1. There is still no automatic system to manage an association between a patient, a nurse, and a mobile medical device that is *implemented and validated*.
2. There are some problems with the use of barcoding systems, such as time required to use them, incorrect/damaged labels, and scanner malfunctions.
3. There are some problems with manual associations performed by healthcare providers, like the high likelihood of errors and the lack of accurate identification, especially for devices.
4. There are some problems related to the unknown location of many mobile devices (pumps, monitors, etc.), especially when they are urgently required.
5. There is no automatic system to control any disassociation between a patient and a device.

In this research, a new approach is presented that aims to overcome the issues mentioned above using an automated real-time patient-device association and disassociation system (RPDAD), which exploits RTLS technology to control and monitor associations between a patient, a mobile medical device, and a provider (nurse). This system also records and notifies any disconnection (disassociation) between the patient and the device. By considering the above problems, the system goals can be defined as in Table 9:

Table 9 System Goals

Goal ID	Goal Description
G1	Automatically track patients with associated devices (IV pumps, cardiac monitors...) in real time
G2	Provide the hospital with an automated interactive system for patient-device disassociation/association.
G3	Eliminate the steps that may cause the errors made by providers during the disassociation/association processes.
G4	Record and notify providers of any disconnection between the patient and the device in near real time.
G5	Provide a simple (mobile) tool for providers to find the nearest available medical devices and manage associations.

4.2. System Requirements

By refining the system objectives and by considering the main scenarios that may happen during the association and disassociation processes, 23 system requirements are defined (Table 10). Each requirement has a unique identifier and is linked to one or more project goals to capture traceability relationships and to ensure full coverage of the goals. These requirements were validated by stakeholders from The Ottawa Hospital.

Table 10 System Requirements

Req ID	Requirement description	Goals
R1	The system shall activate, communicate with, and track a patient's tag and a nurse's badge and also a device's asset tag, whether the device is fixed or mobile.	G1
R2	The user shall have the option to search for the list of patients in her proximity at any time.	G2, G3
R3	The user shall have the option to search for the list of medical devices in her proximity at any time.	G2, G3
R4	The user shall be given a prompt that allows for initialization of patient, provider and device association when the some prompt conditions are met: see Table 11.	G3
R5	The system prompt shall identify the user's name and display the patient name/ names and the asset type (example Vital Sign Monitor)	G2, G3
R6	The user shall be able to confirm the association by selecting the patient name and device name. Example of dialogue: "Nurse Diane, do you want to associate Device X with Patient A?"	G3

Req ID	Requirement description	Goals
R7	The system shall display one or more patient names depending on the number of patients that meet the criteria in requirement R2 and allow the user to select a patient.	G2, G3
R8	The system shall display one or more device names depending on the number of devices that meet the criteria in requirement R3 and allow the user to select a device.	G2, G3, G5
R9	The user's selection of the patient name shall confirm the 3-way association between the device, provider and patient.	G2, G3
R10	The system shall record the information of the association after confirmation in the system database.	G1, G3
R11	The system shall display a message to the nurse; example "Diane, you have associated Device X is with Patient A at time xx:xx and date dd:mm:yy".	G1, G3
R12	The user shall have the option, without selecting any patient name that confirms association, to go back to the previous step which would prompt the system to re-search for conditions stated in requirement R2. In this case the system shall record the information in the system database.	G1, G2
R13	The user shall be prompted to start another association between the same patient and another device once conditions in R3 are fulfilled for another device.	G1, G2
R14	The user should not be able to associate a device to patient B while it is still associated with patient A.	G1, G3
R15	The system shall go back to the home page after an association.	G3
R16	The system shall disassociate an existing association automatically when the equipment moves away from the patient environment (i.e. part 1.b of condition 3 in Table 11 is no longer met). However the system should not disassociate if the provider moves away from the patient (i.e., if part 1.a of condition 3 in Table 11 is no longer met).	G1, G4, G5
R17	When there is an automatic disassociation, the system shall notify the provider about the disassociation.	G1, G4
R18	When there is a disassociation, the system shall record the information of disassociation in the system database.	G1, G2, G4
R19	The system shall show the disassociated device with date and time, when the nurse is not in the room.	G1, G4, G5
R20	Upon disassociation, the system shall give the nurse an option to associate the disassociated device to the same patient or to another patient.	G2, G3
R21	The system shall display the current associations between the patients under the provider's care and the devices.	G1, G2
R22	The system should track the associated patient anywhere, and not only in the patient room as per condition 3, part 1 in Table 11.	G1, G4

Req ID	Requirement description	Goals
R23	The system should track the associated device anywhere, and not only in the patient room as per condition 3, part 2 in Table 11.	G1, G4, G5

Table 11 Prompt Condition

Cond. ID	Condition Description
1	A user/provider is within the patient area as detected by a tuned RTLS beacon and/or Wi-Fi.
2	An asset is within the patient area as detected by a tuned RTLS beacon and/or Wi-Fi.
3	<p>Exceptions:</p> <ol style="list-style-type: none"> 1) In the case where more than one asset falls within the “Patient Proximity” the following rules should be followed to prioritize which asset should be first identified. <ol style="list-style-type: none"> a) Device fixed to the wall should be identified first b) Then mobile devices are prioritized based on closest device to the patient. c) At all times the user should be able to prompt the system to list other devices in the proximity of the patient for selection 2) In the case where two or more providers are in “patient proximity” the system should identify the provider closest to the patient (system gives each provider in the room the prompt until one of them actions it).

4.3. System Architecture

In this section, the structure and behavior of the RPDAD system is discussed, first from the overall structure of system and its components, sub-components and interactions, and then through sequence diagrams to visualize activities and workflows of important scenarios. A database schema is provided to show how the main information is stored. Then, implementation details are discussed.

4.3.1 System Design

Figure 6 illustrates the RPDAD system, which contains four major components including a user interaction system component (C4) for interacting with nurses. The dependencies between the components clarify the type of data being exchanged. The function of each component will be discussed in general in this part.

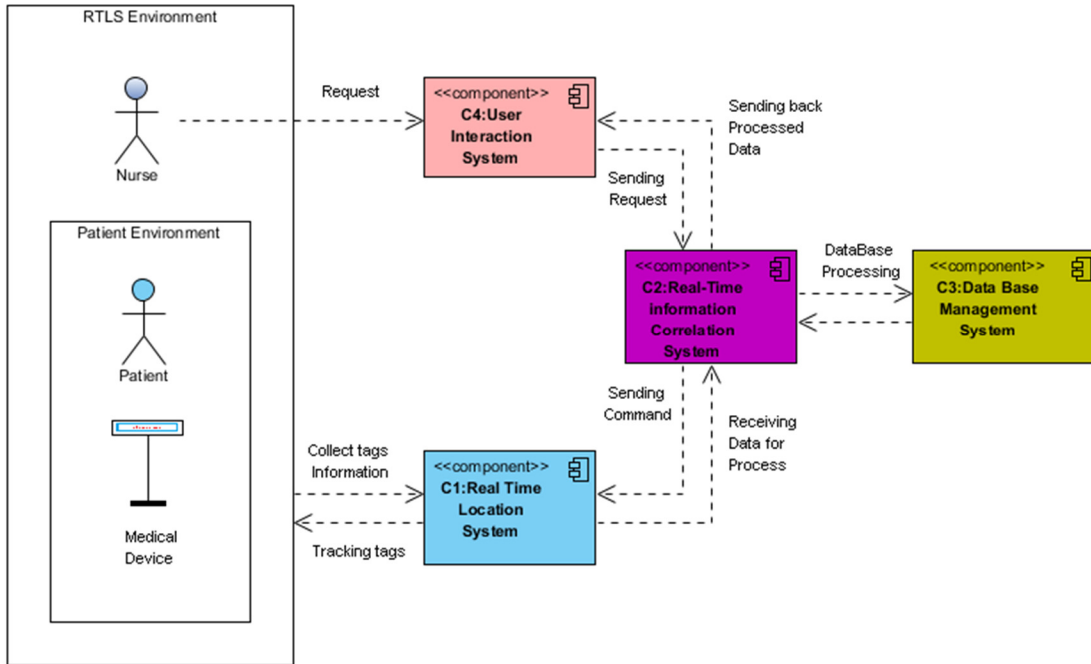


Figure 6. Abstract High-Level System Architecture

C1: Real-Time Location System (RTLS). This component provides a solution for finding the location of all necessary objects under a specific environment (RTLS). Also, this component is used to track the location of some objects that have to be under control in real time. According to the RTLS framework, the RTLS has its own subsystems that include RFID tags, RTLS database, and RTLS server controller, as presented in Figure 7.

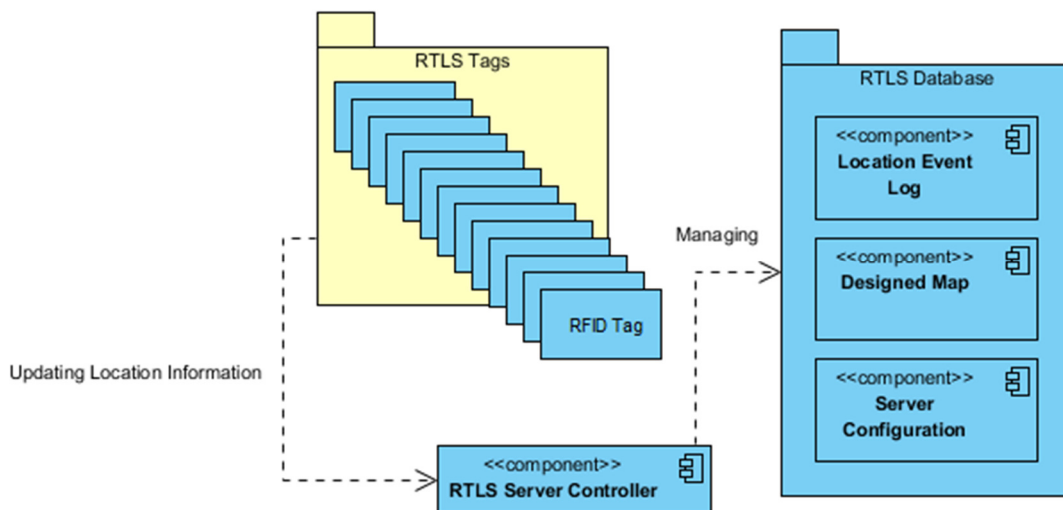


Figure 7. Real-Time Location Component (C1)

RFID tags are responsible for tracking physical resources, and they should be configured by the server controller. The RTLS server controller configures them in terms of network access credentials, network channels, server IP addresses, etc. Actually, the server manages not only tags, but also other RTLS subsystems and functions, such as uploading designed maps, and monitoring system event logs stored in the RTLS database package. Generally, the RTLS database stores all received location information, which is useful for our case to calculate distances between a device and its associated patient and make a decision for disassociation detection.

C2: Real-Time Information Correlation System. This core system basically links all components together. It controls and manages all requests by recognizing the request and the sender source (component) and providing a suitable answer back to the sender. As a result, this component should be always listening to defined ports in order to communicate with other components, as shown in Figure 8.

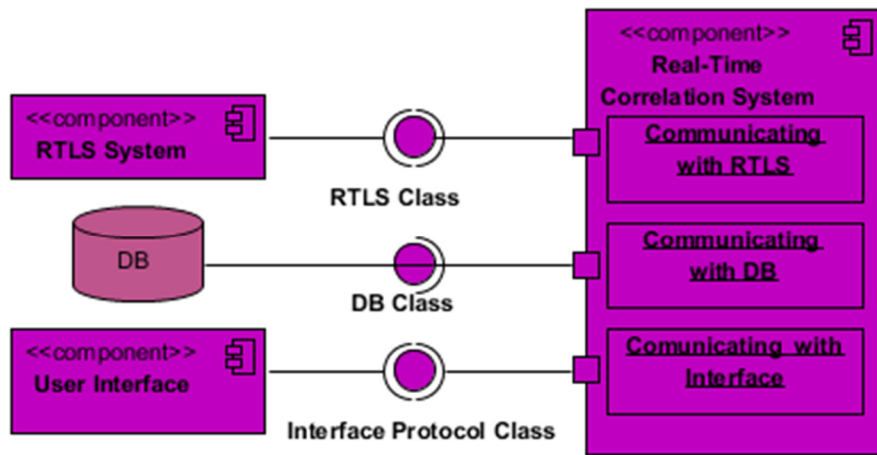


Figure 8. Real-Time Information Correlation Component (C2)

As implied by the requirements, there is just one type of request needed, but for different purposes. The information correlator has two purposes: for any patient-device *association*, the request is fetching the location of necessary objects at a specific time and the time of request, whereas for any patient-device *disassociation*, the request is fetching the location of specific objects constantly, but with a pre-defined time cycle (polling).

C3: Database Management System. This component is interacting only with the information correlator component and manages all requests sent by the latter. Basically, retrieving and storing data are its main responsibilities.

C4: User Interaction System. This component is the only component visible the healthcare provider, for inputs and outputs. This component also interacts with the real-time information correlator. Actually, this component generates most of the requests capturing the end-user needs.

4.3.2 System Scenarios

Interpreting the user-related requirements, there are several main activities that have to be done by a healthcare provider (user) and by the system. The only user that is interacting indirectly via an interface (mobile application) with the system is a healthcare provider. From this point on, when we say “system”, we mean RPDAD with all of its components (as discussed in section 4.3.1). In order to clarify operational concepts from the requirements, two Use Case Map diagrams [3] are provided to characterize the general processes, while four sequence diagrams extracted from these Use Case Maps are provided to refine each important feature from the user’s perspective.

In this part of system architecture, the expected scenarios for associations and disassociations are provided individually, with the functionalities and components involved. As shown in Figure 9, the P2D association starts with a healthcare provider (nurse) who starts the mobile application (the client, also called tablet application). Upon starting, the mobile application first sends the request for the closest device and patient to the core system (i.e., the RPDAD server). When such request is received, the RPDAD generates appropriate messages and sends them to the RTLS, which then returns the appropriate object locations (from the room) to the RPDAD server. The latter calculates distances and finds the options closest to the requesting nurse, and sends them to the nurse’s mobile application. At this time, the nurse must accept the suggestion or reject it. In the latter case, all devices and patients in the room are provided to the nurse, which can then select one of each kind on the mobile application.

At the end, the nurse accepts/confirms the association and the RPDAD server stores it in its database. As mentioned in the problem description, the current methods for associating a device to a patient and a provider (typically a nurse) are barcoding systems and paper-based associations. Therefore, our system must avoid any time-consuming nurse activity in order to compete with these methods.

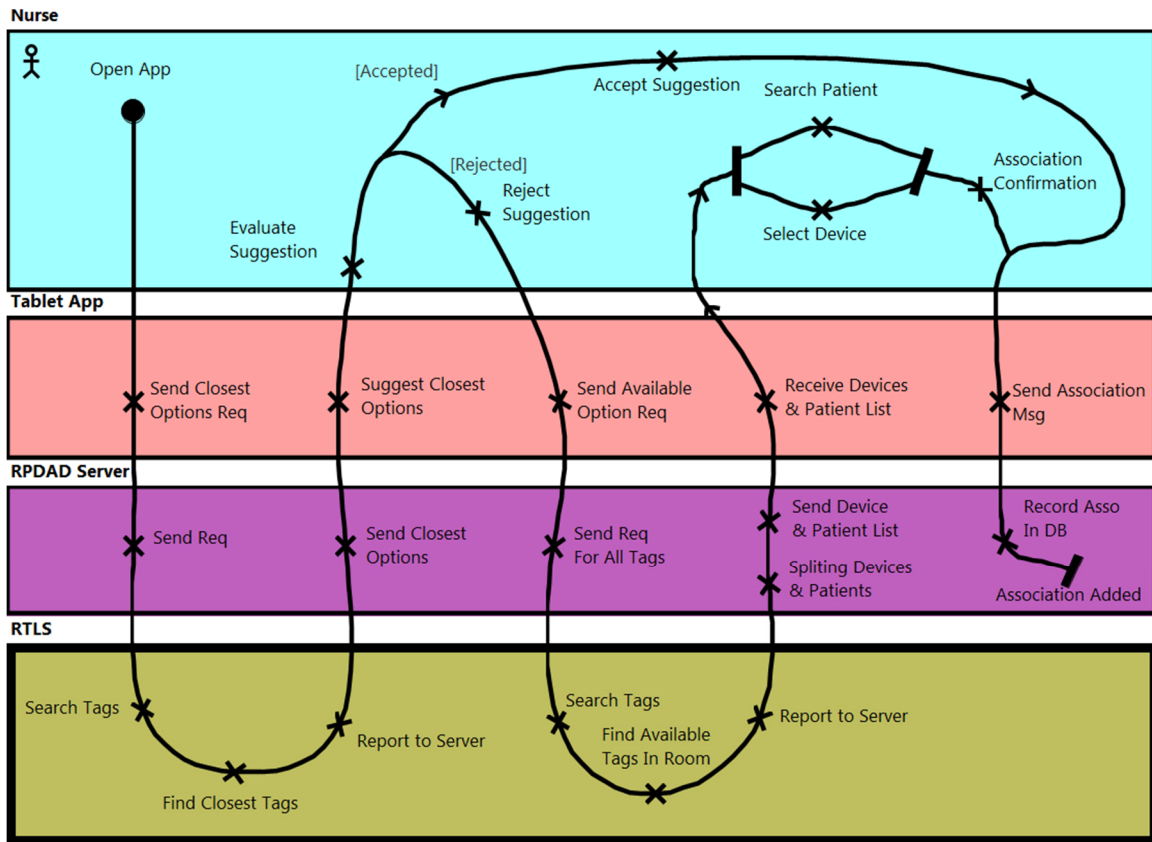


Figure 9. P2D Association Process

Figure 10 shows the disassociation process, either manually done by nurse or automatically done by the system when it detects too large a distance between associated patient and device. Clearly, for a manual disassociation (used when the nurse has to assign the device to another patient or when the device work is finished), there is no need to communicate with the RTLS. When a nurse’s disassociation request sent via the mobile application is received by the RPDAD server, the latter updates the database. The automatic disassociation process starts inside the RPDAD server, which checks all associated patient-device pairs in the database at cyclic time intervals and compares their distances re-

ceived from the RTLS in real time. If they are not close enough according to a preset distance threshold (configurable in our system), the RPDAD server will consider their association to be broken, update the database, and report this disassociation to the mobile application to alert the nurse.

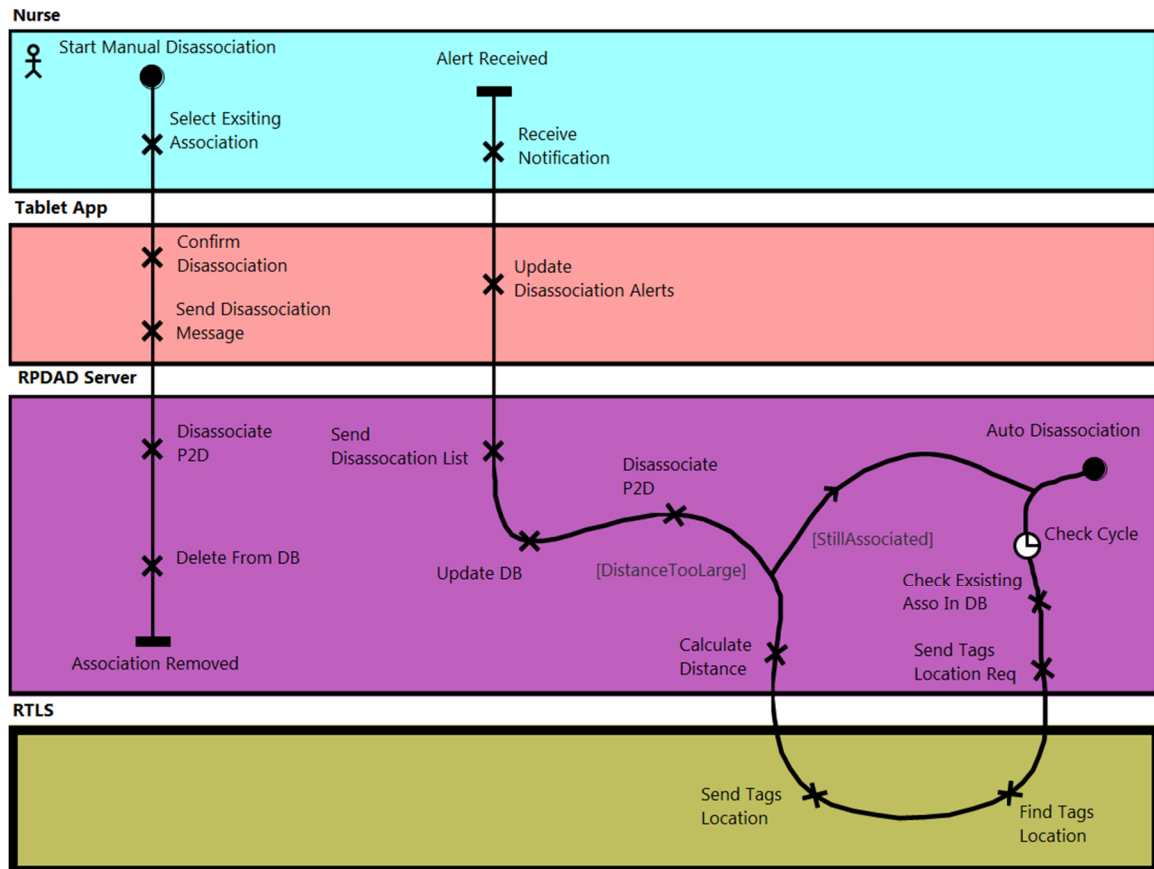


Figure 10. P2D Disassociation Process

For a more detailed view, the logic of each activity and branches has been formalized in the Use Case Map model with the jUCMNav tool [42]. Four scenarios are particularly important and they are described below with sequence diagrams generated from the Use Case Map model using jUCMNav [34]. These scenarios include:

- The acceptance of an association suggestion proposed by the RPDAD system.
- The rejection of the suggested association, followed by the selection of a specific device to associate to a specific patient in the room.
- A manual disassociation initiated by the nurse.

- The automatic disassociation of a device found to be too far from its patient.

Accepting an association suggestion: As Figure 11 illustrates, the nurse can start this activity by opening the mobile application, then the server receives the request and sends back its suggestion for the closest patient and closest device, for a potential association. As soon as the nurse accepts the suggestion, the association message is sent to the server and the device and the patient become associated.

Rejecting a suggestion: As Figure 12 shows, once the nurse has opened the mobile application, the server receives the request and sends back its suggestion for the closest patient and closest device, for a potential association. This time however, the nurse is not interested to follow the suggestion and she wants to associate other options together. When the nurse rejects the suggestion, the server sends back all available options, whether patients or devices. As a result, the nurse must select a patient and a device (in any order) to associate. The nurse can then confirm the association. Subsequently, the system receives the association information and the device and the patient become associated. At any time, the nurse can cancel the association, but in this case, no message will be sent to the server.

Manual disassociation: As Figure 13 highlights, the nurse can select an existing association to disassociate and confirm her intent. Consequently, the server will receive a disassociation message and remove the association between the device and its assigned patient.

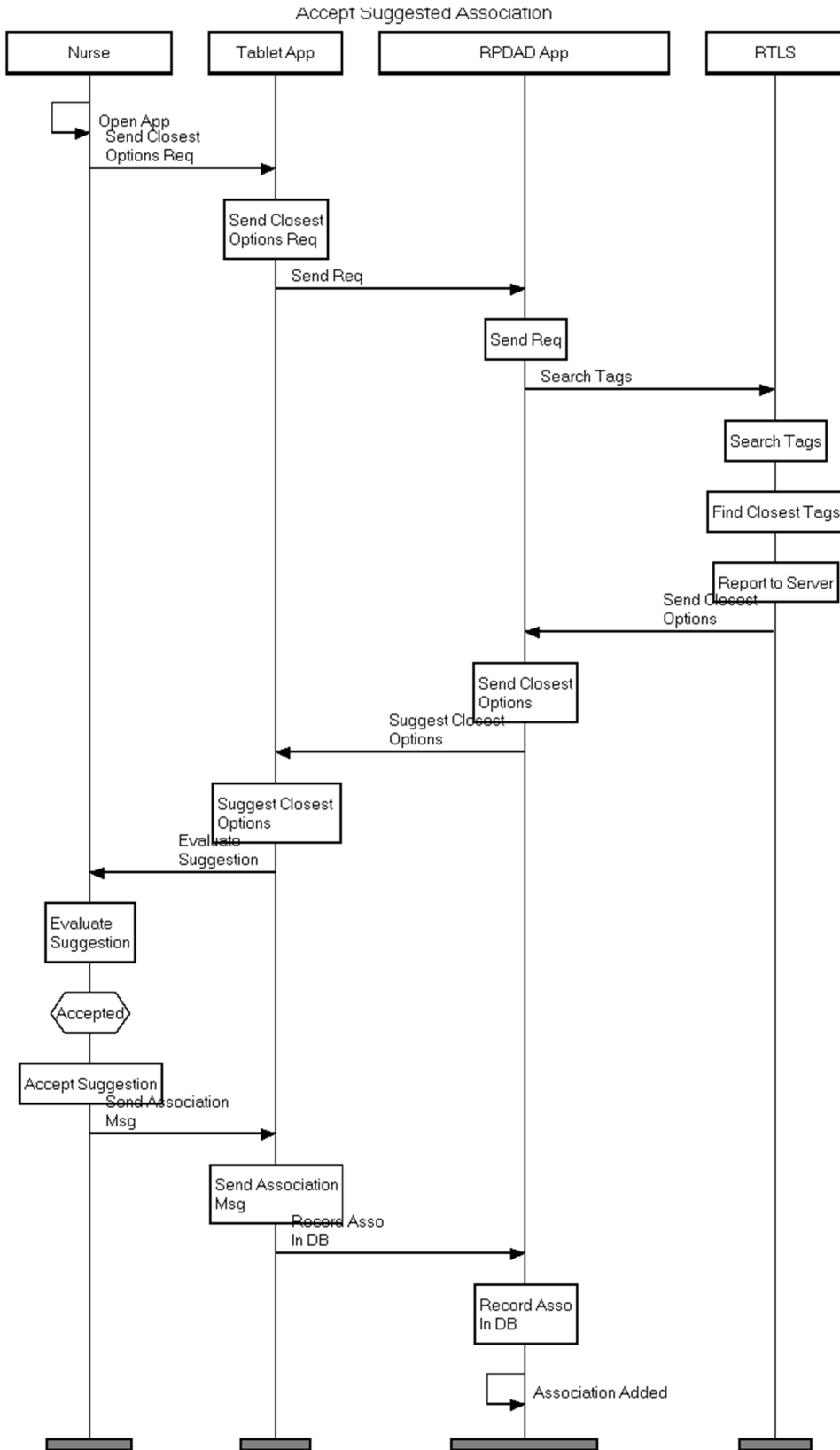
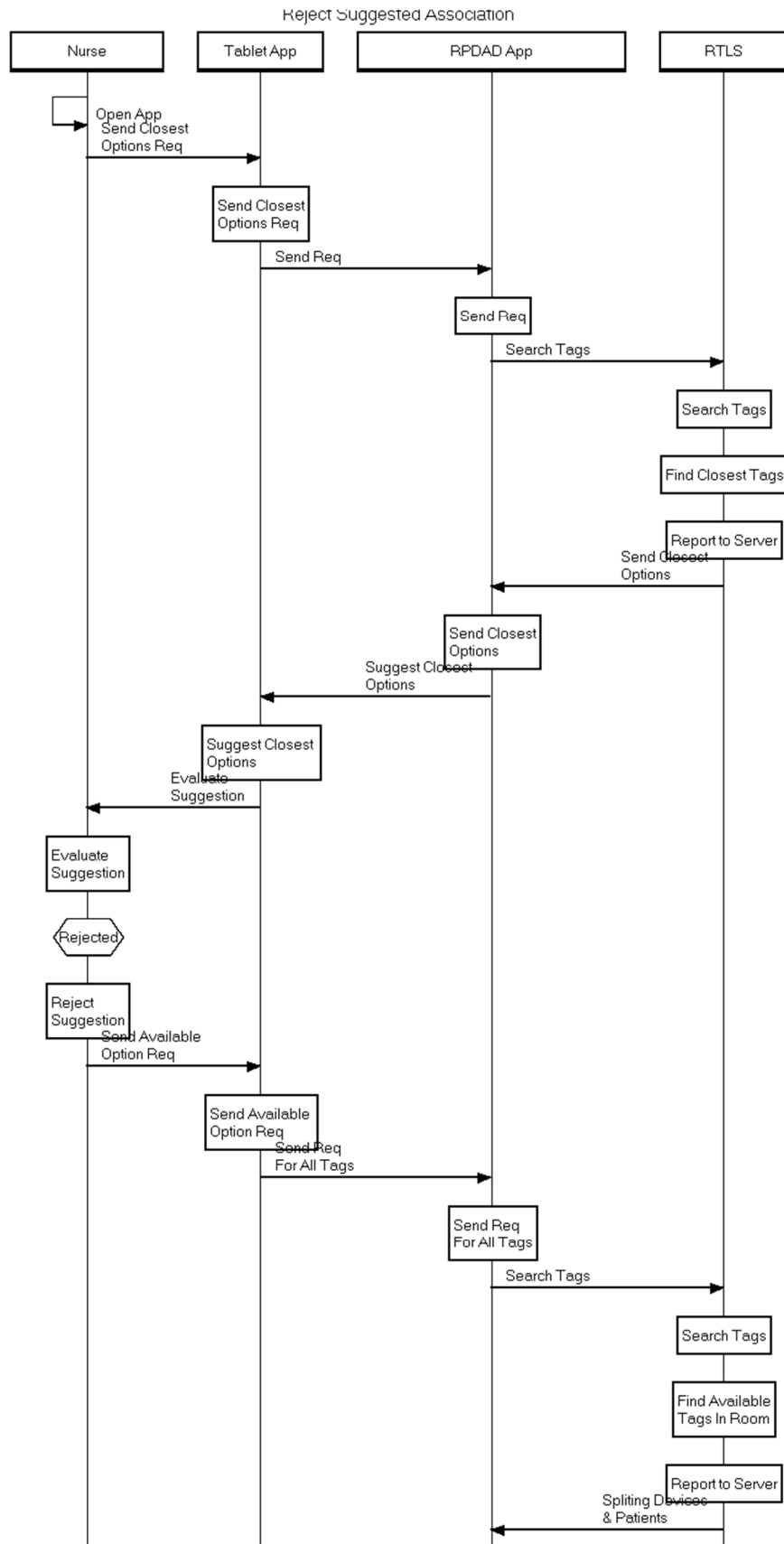


Figure 11. Accepting an Association Suggestion – Sequence Diagram



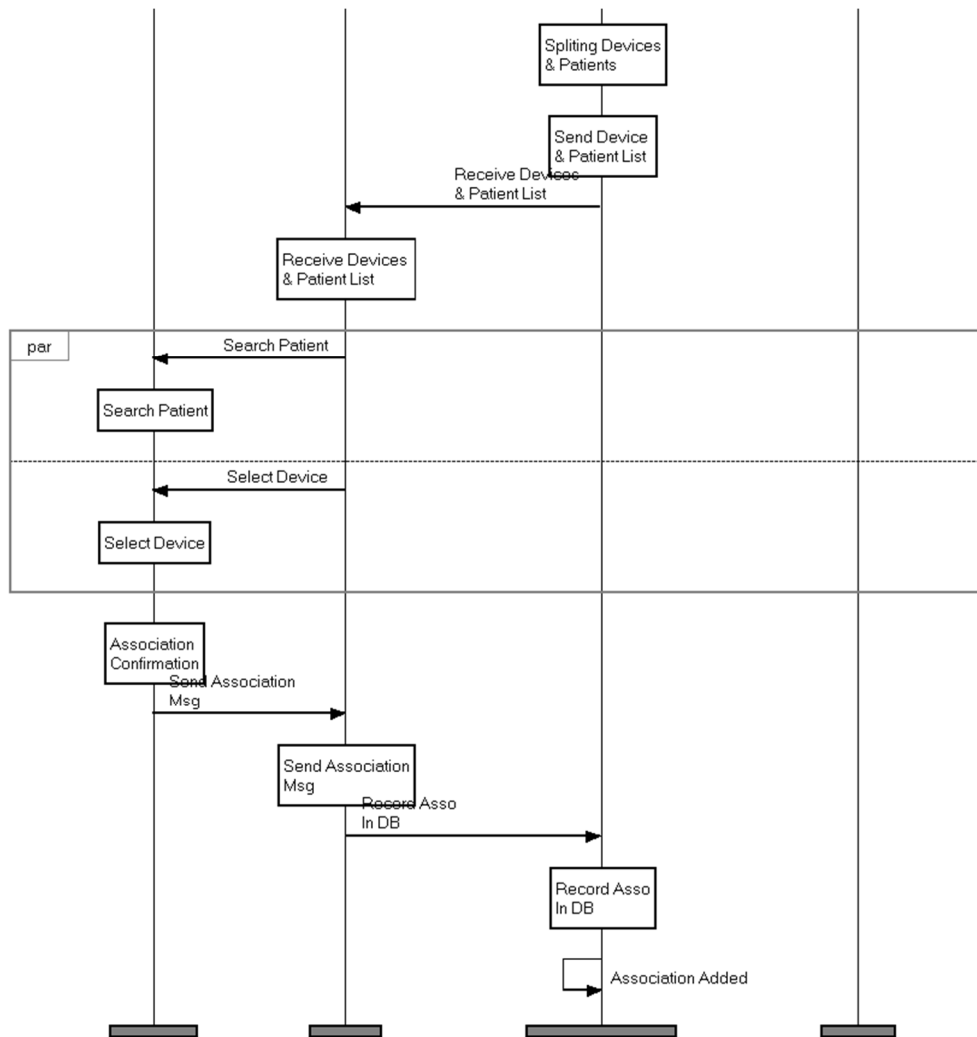


Figure 12. Rejecting an Association Suggestion – Sequence Diagram

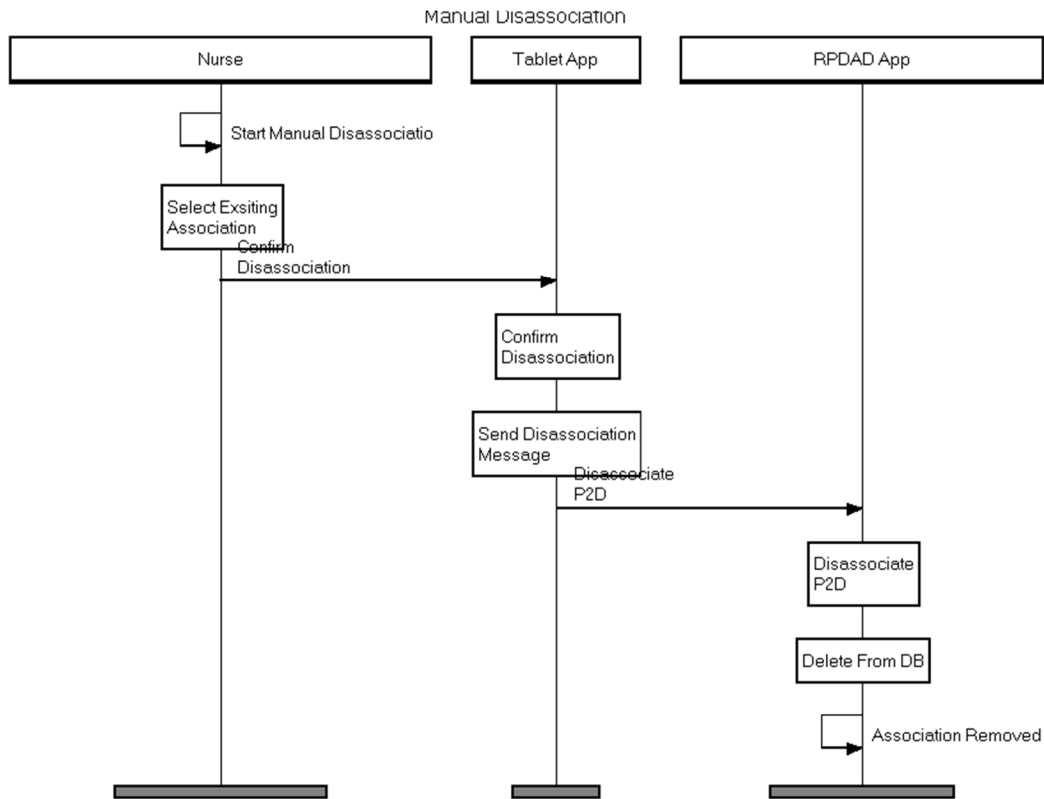


Figure 13. Manual Disassociation – Sequence Diagram

Automated disassociation with alert notification: In this situation, despite all activities that could be activated by the nurse, the system captures this event when an automatic disassociation happens (if the assigned equipment moves too far away from the patient environment, something that is checked by the server at specific intervals), updates the database, and sends an alert notification to the nurse. Figure 14 provides the details of this scenario.

So far, the architecture and main functionalities of the system have been provided to make design concepts understandable before going into the implementation. The next section adds implementation details, including the configuration of a specific RTLS (Ekahau’s), the design and implementation of the mobile client application, including its user interface, and a database schema.

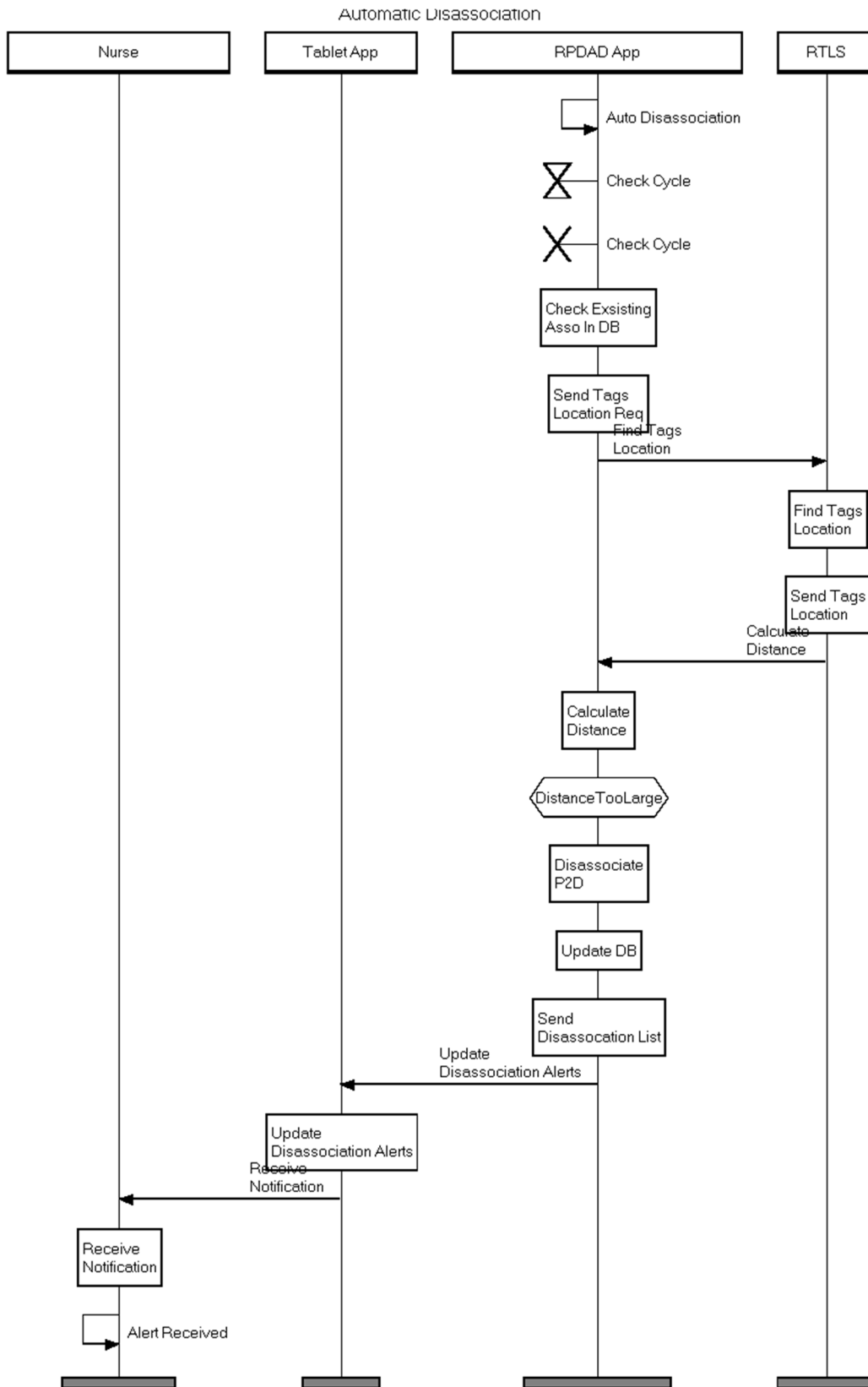


Figure 14. Automatic Disassociation – Sequence Diagram

4.4. Implementation Details

After designing the system and clarifying its abstract architecture and scenarios, the system is now ready to be constructed. Appropriate technologies and protocols need to be selected to instantiate the abstract components and connections defined in the previous sections. Given the constraints imposed by the partner hospital and the availability of suitable equipment in our laboratory, the technology used as real-time location system is Ekahau's RTLS technology. In Figure 15, the sub-components of Ekahau's system are shown as two complementary packages: Ekahau RTLS package and Ekahau RTLS tags. The RPDAD server component is a custom made application programmed in Java (because the Ekahau RTLS offers Java APIs) and the client tablet application is programmed in Java as well, as this is a frequently used language on the Android OS, a platform selected for its ease of deployment (and because we had Android tablets available for testing). For the database engine, Microsoft SQL Server was selected as the thesis author was familiar with this technology (but any database management system would work here). These components and packages are detailed in the next sub-sections.

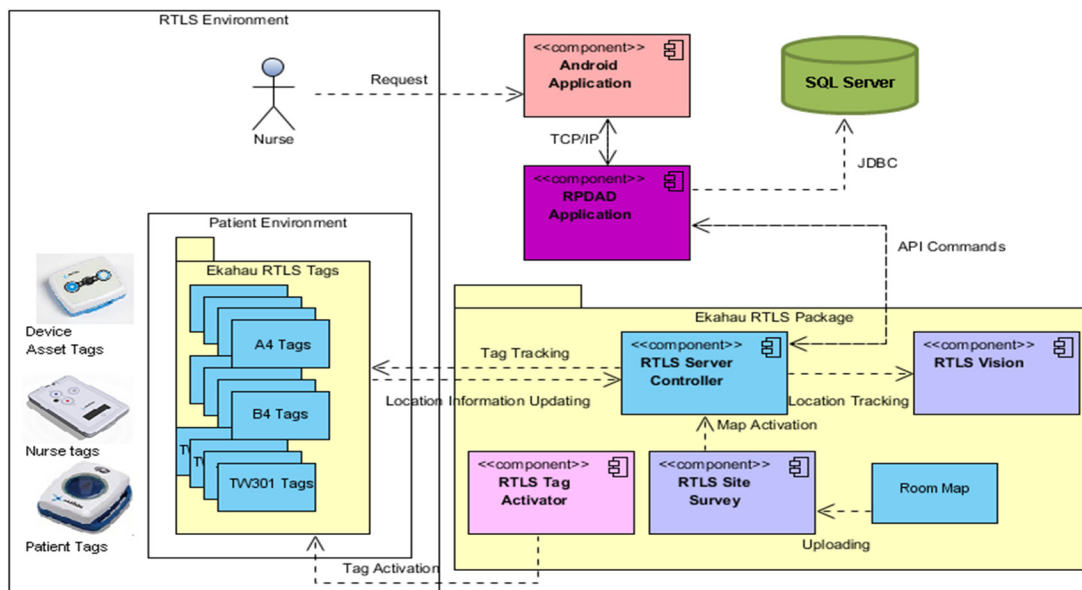


Figure 15. RPDAD System Architecture

4.4.1 Ekahau RTLS Package

RTLS Tag Activator: as the name indicates, this subsystem is responsible for the activation of location tags. Before running Ekahau's RTLS, tags should be activated to be tracked, and this step needs software and hardware configurations. Before using the activator software, a NIC-300 PCMCIA network adapter should be installed on the laptop computer where this software has been already installed. Then in the software, the Ekahau RTLS controller (ERC) IP address, the maintenance interval, as well as wireless network settings such as the Service Set Identifier (SSID), security (open, WPA2-PSK, and WEP supported), and tag IP settings should be set up. When the activator is put into activation mode, using a specific way for each type of tags, the activation process is completed. If this process is successful, the tag can be seen in the activator screen. Also, once the tag is activated, it can be shown in the server controller console (ESS) in order to be tracked.

RTLS Site Survey (ESS): this subsystem is for creating and editing a positioning model to enable accurate location tracking in order to calibrate the RTLS environment. In addition, analyzing the wireless network, optimizing location tracking accuracy and defining the environment and zones can be done by the ESS. As Figure 15 shows, a map of the room should be provided and uploaded in the ESS. However, the NIC-300 PCMCIA adapter should be used while this software is working.

RTLS Vision: this subsystem is an end-user application for grouping, locating and viewing the location of people and assets in real time, for monitoring events, and for invoking notifications or alarms. The main usage of the Ekahau Vision software platform and interface is for tracking, mapping, messaging, reporting, and managing locations in real time. With Vision, one can gain visibility into the location of individual assets and groups of assets.

RTLS Server Controller: this server software is used for location tracking, Wi-Fi tag configuration and management. Basically, the Ekahau RTLS Controller has an easy-to-use web-based user interface and it provides wireless configuration of Ekahau Wi-Fi tags

and system administration. The tags can be assigned into groups to support various tag management and deployment activities. Also, this controller can receive signal strength measurements from Ekahau Wi-Fi tags, and can calculate accurate location estimates. Furthermore, this application can be integrated to any custom-made application by using application Programming Interface (API) commands. As a result, our server application (RPDAD) can communicate directly with this application through API commands to receive the locations of tags, process them and send them to the mobile application.

4.4.2 Ekahau RTLS Tags

As discussed in section 2.3.4, Ekahau RTLS tags can be assigned to objects. In this case, there are three types of tags:

- **A4 Tags:** (asset tags) are designed to be installed on medical devices that should be tracked. A4 Wi-Fi tags transmit data to the ERC, which determines asset location and status.
- **B4 Tags:** (badges) are designed for employees, in hospitals for healthcare providers, and they can be worn around the neck on a lanyard or using a belt clip. Not only are B4 badges used for nurse tracking, they can also receive and send text messages using simple two-button LED display screen controls.
- **TW301 Tags:** (patient tags) are designed to be worn by patients, employees, children and other individuals, which should be tracked under the RTLS environment. They enable real-time visibility into a persons' exact location. They can be washed and sanitized.

4.4.3 RPDAD Server

As discussed before, this component acts as a core system, which means it can be a bridge for data transfer and processing between components. In other words, this component supports different functionalities and communication types. This server is a Java-based custom-made application server that receives streamed events by API commands from the RTLS server and that sends location request to the RTLS server. By calculating the distances between associated objects, it can feed the mobile application requests via

sockets (TCP/IP), and can transfer all changes to the database simultaneously using Java Database Connectivity (JDBC).

4.4.4 Mobile Client

A Java-based application with a specific graphical user interface was developed in Java for the Android OS, and tested on a Samsung tablet. The details of this mobile client, which interacts with the user and with the RPDAD server, are provided in section 4.5.

4.4.5 Database Schema

As can be seen in Figure 16, the database designed with Microsoft SQL Server includes six tables.

Three tables are used to store the information of different types of objects. Each device is defined by its ID, which is the MAC identifier printed on the device tags, the name of device and the current location of device. The patient table and the provider table have similar fields (with IDs coming from the hospital information system), but for a provider, the role should be identified as well (nurse or physician).

There are three other tables designed to record the association / dissociation information. The *current association* table is storing all existing associations involving a provider, a patient and a device. The *new disassociation* table records any automatic disassociation currently being notified to the responsible provider. If the provider receives a disassociation notification and checks it out, the corresponding record of disassociation will be removed from this table and will be added in the *old association* table. The old association table keeps a log of all associations that existed, which is useful for reporting and data mining. Obviously, if any disassociation happens, the system must ensure that its data is removed from current association table.

In these tables, the identification of all objects (provider, device, patient), the time and date of association/disassociation and the location of each object are recorded. In the current association table, there is also an extra field, *AssString*, which encodes all relevant information about the association, to be used in data transfer between the mobile application and the RPDAD server.

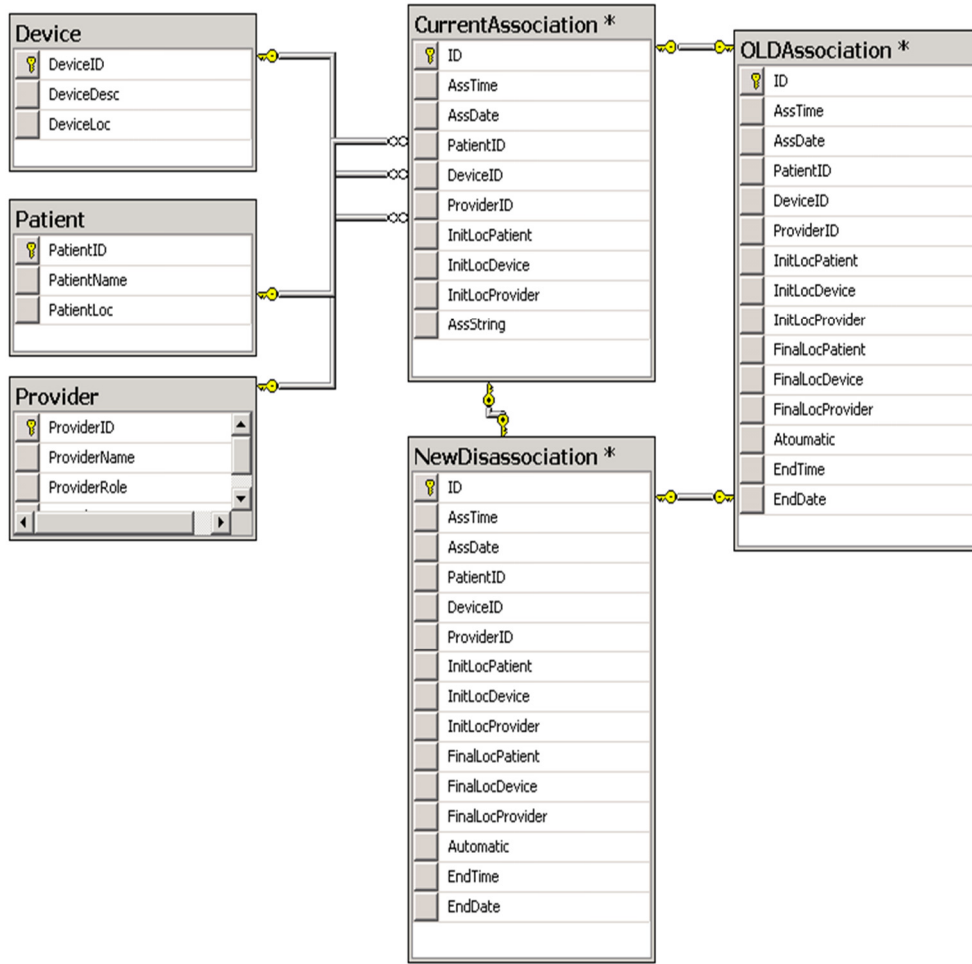


Figure 16. Database Schema

4.5. Mobile Client (Tablet) Application Design

This section discusses the design, user interface, and communication messages of the developed mobile (tablet) application.

4.5.1 Mobile Application Design

As mobile applications are convenient ways for healthcare providers to perform their tasks, we propose an Android (mobile) application as a user-friendly interface for tracking patient-device associations and disassociations. The high-level design, shown in Figure 17, illustrates that this application communicates with the RPDAD server through

sockets. Many instances of this application (e.g., running on different tablets or phones) can co-exist, which help support multiple nurses in their work.

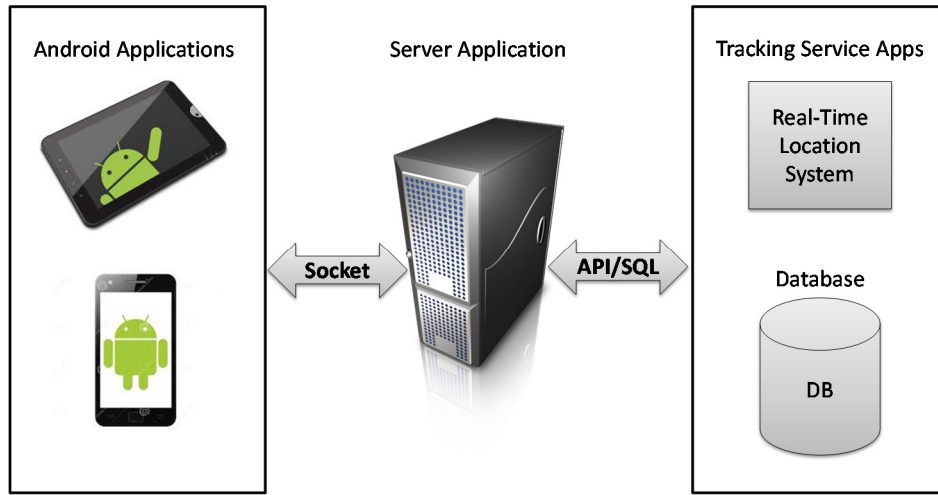


Figure 17. Mobile Application Design

The mobile application is meant to be used by healthcare providers. Figure 18 presents the four main usage scenarios supported by the application, from the viewpoint of the nurse. The next sub-section will present the multi-tab user interface supporting these scenarios.

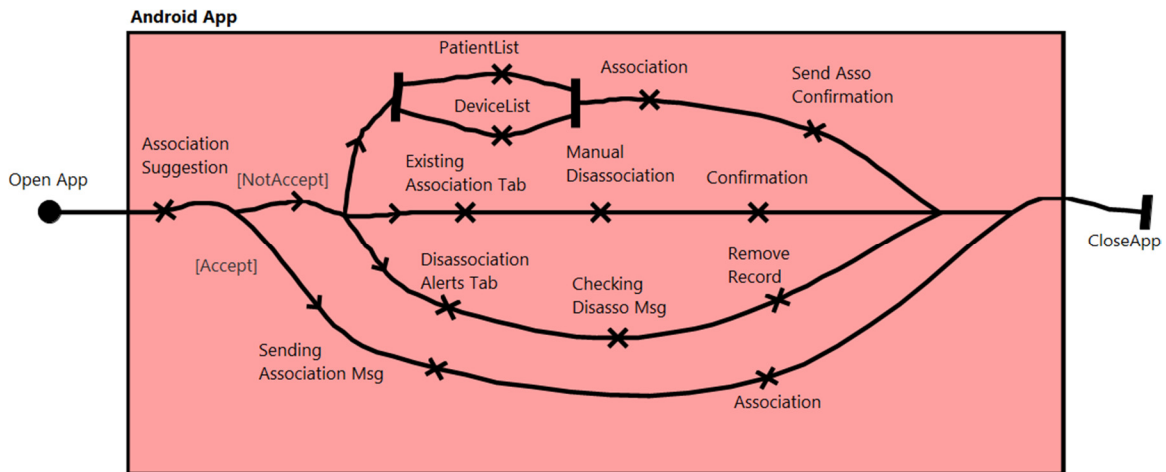


Figure 18. Mobile Application

4.5.2 User Interface

A fundamental reality of mobile application development is that the user interface (UI) is the main layer used for communicating with users. Hence, it should allow users to

achieve their goals quickly and easily. If the end-users find the software to be too difficult to understand, then an excellent product could still fail. Therefore, in our solution, we attempted to ensure that the nurse using the mobile application does not waste time. Figure 19, Figure 20, Figure 21, and Figure 22 illustrate the usage scenarios for this application.

Figure 18 implies that there are four end-to-end functionalities for a nurse to choose from. For example, after opening the application, a suggestion message to associate the closest patient and device is automatically presented to the nurse (Figure 19, left). If the nurse accepts this proposed default association, she will receive another message for confirmation. By accepting this confirmation, the default association will be created and added to the database by the RPDAD server (Figure 19, right). Otherwise, the nurse is presented another window, which is the content of the first tab (NEW) of the mobile Android application (Figure 20, left). In this window, all available patients and medical devices are presented in two lists. The nurse can choose one of each and then confirm the association (Figure 20, right).

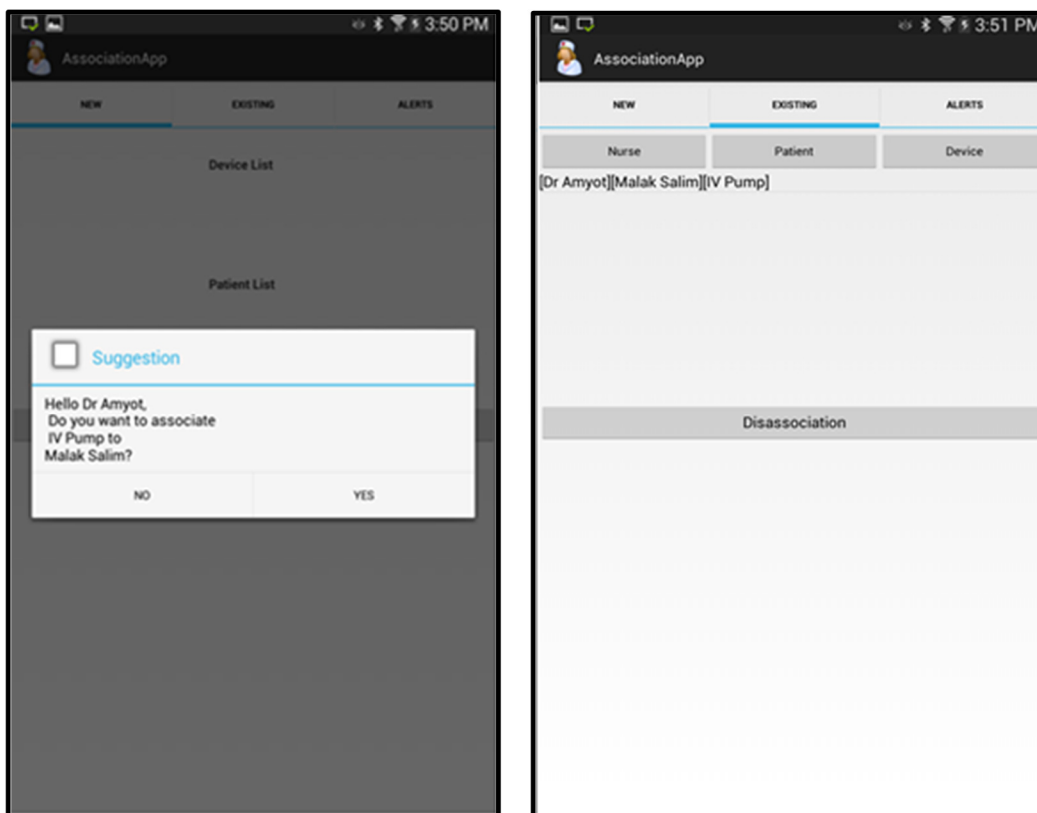


Figure 19. Association Suggestion

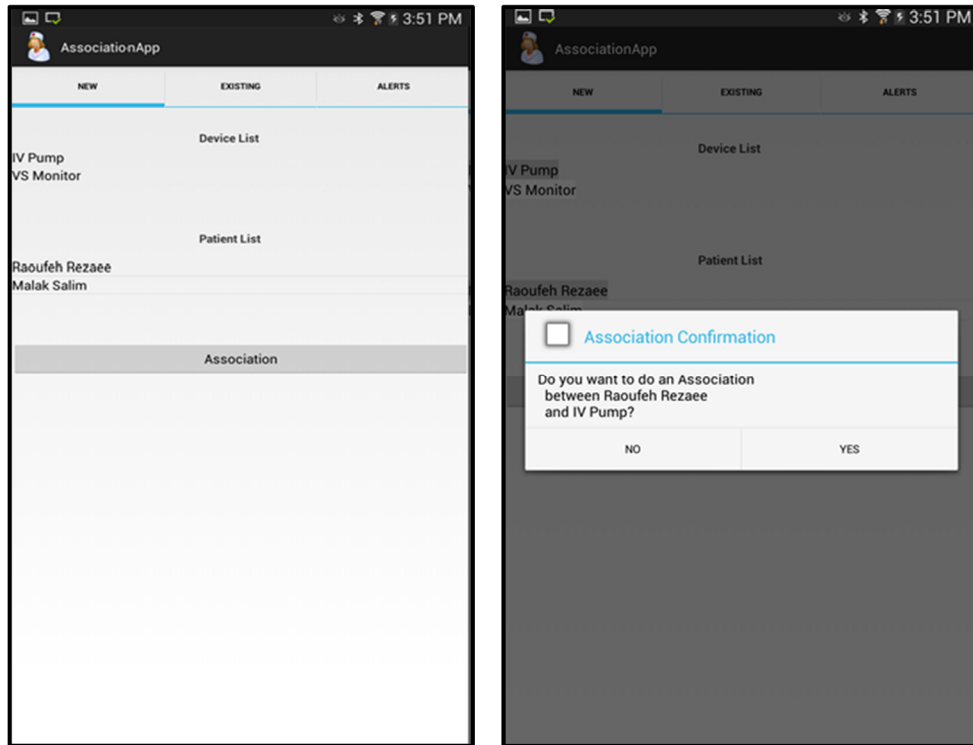


Figure 20. Regular Association and Confirmation

In Figure 21, which shows the content of the EXISTING tab, the existing associations are listed and can be sorted by nurses, patients or devices. Also in this tab, a manual disassociation can be requested by selecting an existing association, and then by confirming.

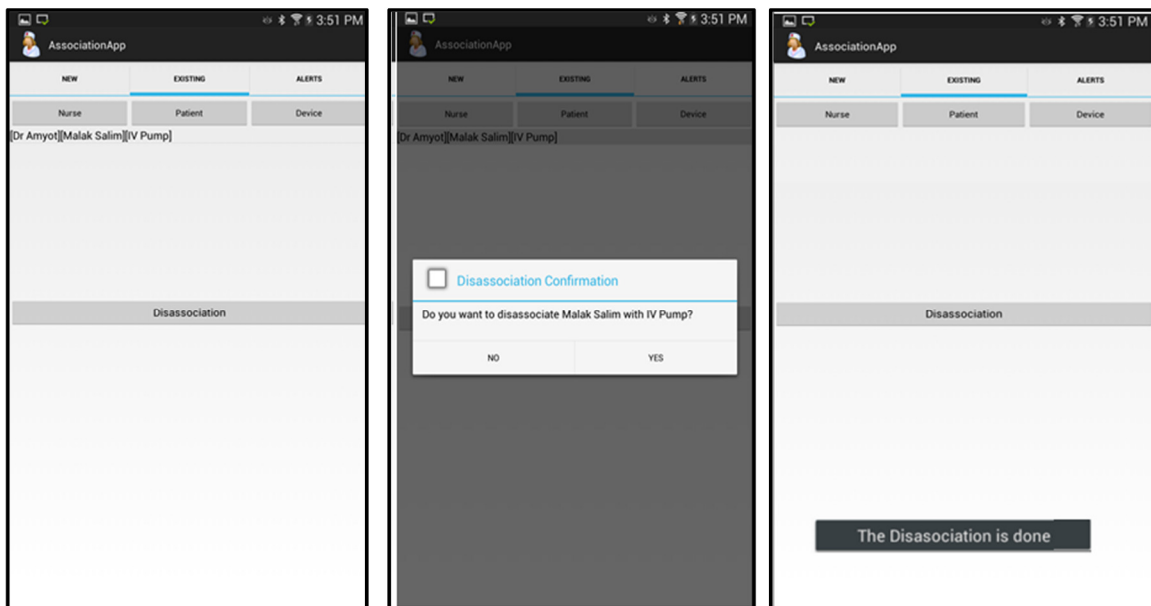


Figure 21. Existing Associations and Manual Disassociation

In Figure 22, third tab of the Android application (ALERTS) shows the disassociation history that has not been noted yet by the nurse. The latter is able to remove alert notifications by clicking on them (hence acknowledging their proper reception). Internally, the RPDAD server transforms the selected new disassociation record to an old disassociation record (refer to the database schema in Figure 16).

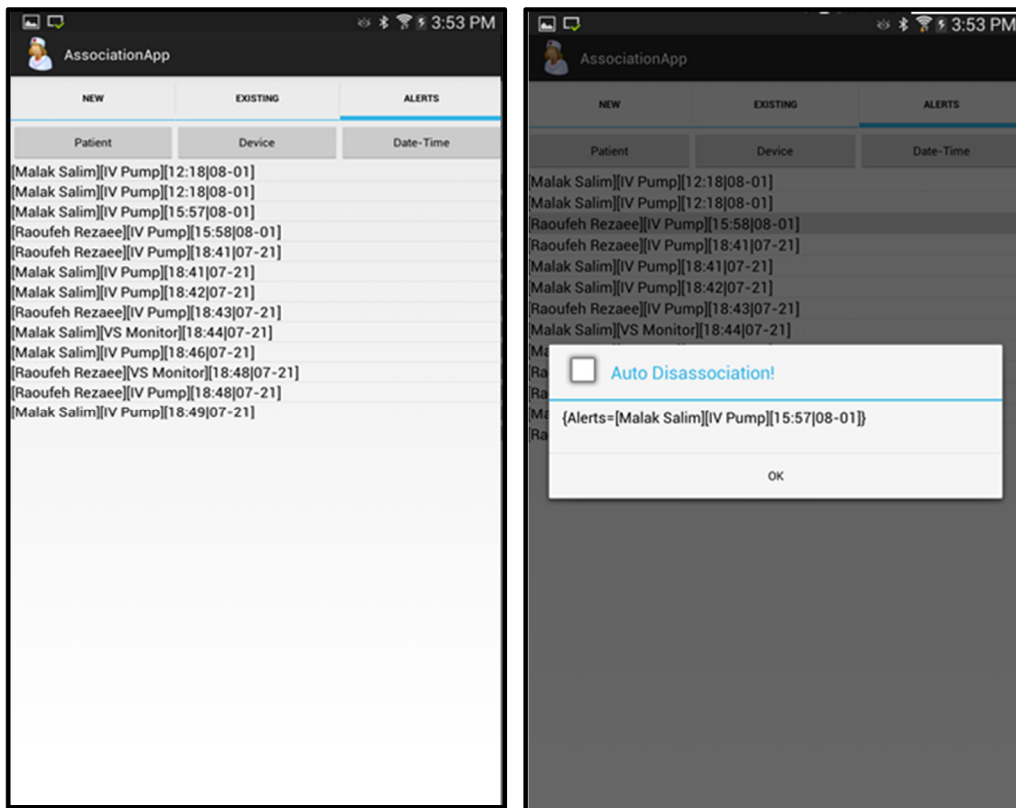


Figure 22. Disassociation Alerts

As can be seen in the previous screen captures, in all three tabs, the Android list view is used because it can show items in a vertically scrolling list. Basically, this view is associated with a simple adaptor, list adaptor, or array adaptor. This choice was superior to Android's grid view, and also enabled re-sorting the content according to different criteria (e.g., through the Patient, Device, or Date-Time buttons in Figure 22).

4.5.3 Communication Technology

There are several ways to communicate with a smart mobile device, such as Bluetooth, Wi-Fi, 3G, and several others. For the Wi-Fi situation (as in this project), socket programming is a common way to support communication, with discrete messages sent from the sender to the receiver either with connectionless datagram sockets (UDP) or connection-oriented stream-mode sockets (TCP).

In our system, socket programming was used with TCP. This choice is more reliable than using UDP communication, without a major performance difference when used over a local network. In such context, there is a need to define the types of messages exchanged between the Android mobile application client and the RPDAD server application (Figure 17). First, the possible messages to be sent and received, which were necessary for the Android application, have been organized and specified, together with their parameters (Figure 23). Then, several streams have been provided. Our solution enables mobile application connections to the RPDAD, hence supporting multiple nurses working concurrently.

- Send:[1][ClosestOptions]
Receive: [1][Nurse, Patient, Device]
- Send:[2][AvailableOptions]
Receive: [2][Patient1, Patient2, Patient3,..., Device1, Device2, Device3,...]
- Send:[3][Nurse][Patient][Device]
Receive: [3][Association]
- Send:[4][AssociationList]
Receive: [4][Nurse][Patient1][Device1], [Nurse][Patient2][Device2],...
- Send:[5][AssociationInfo]
Receive: [5][ManualDisassociation]
- Send:[6][DisassociationList]
Receive: [6][Patient1][Device1][DateTime1], [Patient2][Device2][DateTime2],...
- Send:[7][DisassociationInfo]
Receive: [7][Delete]

Figure 23. RPDAD Communication Messages

4.6. Chapter Summary

This chapter provided details of the RPDAD architecture. It started by identifying goals and requirements in order to simplify the design phase, then an overview of the abstract system architecture with its components was given. At the end, by identifying the main scenarios, additional implementation details were discussed. The discussion covered the RPDAD server side, the mobile Android client side, and the communication protocol between them. Going back to Table 10, the RPDAD system currently supports all requirements except R13 (re-association can however be done through the interface in the NEW tab).

The next chapter will present the deployment and experimental validation of RPDAD with an analysis of the main results.

Chapter 5. Deployment and Experimentation

This chapter presents the validation strategy for the RPDAD system and the results. First, the details of the deployment of RPDAD in a university laboratory and at a real hospital, used as a proof of concept, are discussed. Then, relevant test scenarios are defined to offer a comprehensive experimentation of the system's capabilities. The steps of this experimentation phase are explained in order to unveil major challenges faced during the development. Finally, the test results are analyzed and assessed.

5.1. Deployment and Demonstrations

Since this research project was conducted at The Ottawa Hospital (TOH) and the University of Ottawa, two demonstrations were given (one at each location) during the development of RPDAD, not only for following the project progress, but also for evaluating the feasibility of the system.

5.1.1 Laboratory Setup at the University of Ottawa

The first demonstration was held in a laboratory of the University of Ottawa in November 2013, in the presence of TOH staff and other students. The objective was to show that the communication between the RPDAD server and the RTLS could be established through the use of the RTLS' API commands (as seen in Chapter 4). The RTLS environment configuration was done and the system was run using a simulated hospital room to demonstrate the association process and the automatic disassociation. At that time, there was no end-user interface (Android client application), and the server console was used to monitor the server's activities.

5.1.2 Patient Room Setup at The Ottawa Hospital

In the second demonstration, in April 2014, the system was deployed in a two-bed patient room at The Ottawa Hospital. As shown in Figure 24, the RTLS server communicated with a private Wi-Fi network composed of a router and two access points (for triangulation). We also installed infrared beacons in the corridor and at the head of each bed, for a higher accuracy (as otherwise, the resolution of the Wi-Fi location would not distinguish between the two beds). We equipped mobile IV pumps and monitors with asset tags, (mock up) healthcare providers with badges, and two (mock up) patients with patient tags. As we were on a busy floor, the system was in a realistic environment in terms of interferences. Moreover, at this time, an Android application had been defined as an interface to make the system more usable and understandable.

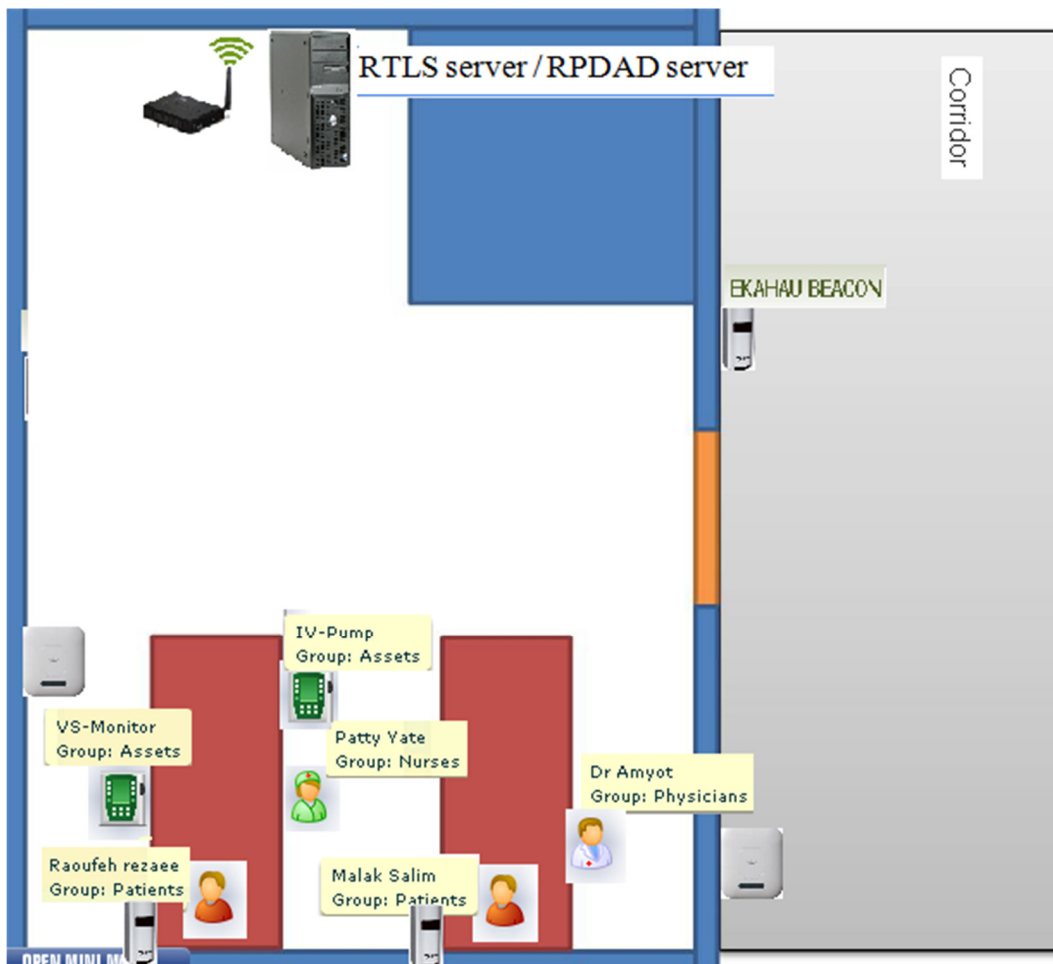


Figure 24. Deployment of RPDAD (Ekahau Map)

In order to test RPDAC's logic and accuracy, and according to the system design details (section 4.4), two expected scenarios have been constructed that cover two forms of association (accepting the association suggestion, and rejecting the suggestion and selecting another one from available options) and two forms of disassociation (manual and automatic).

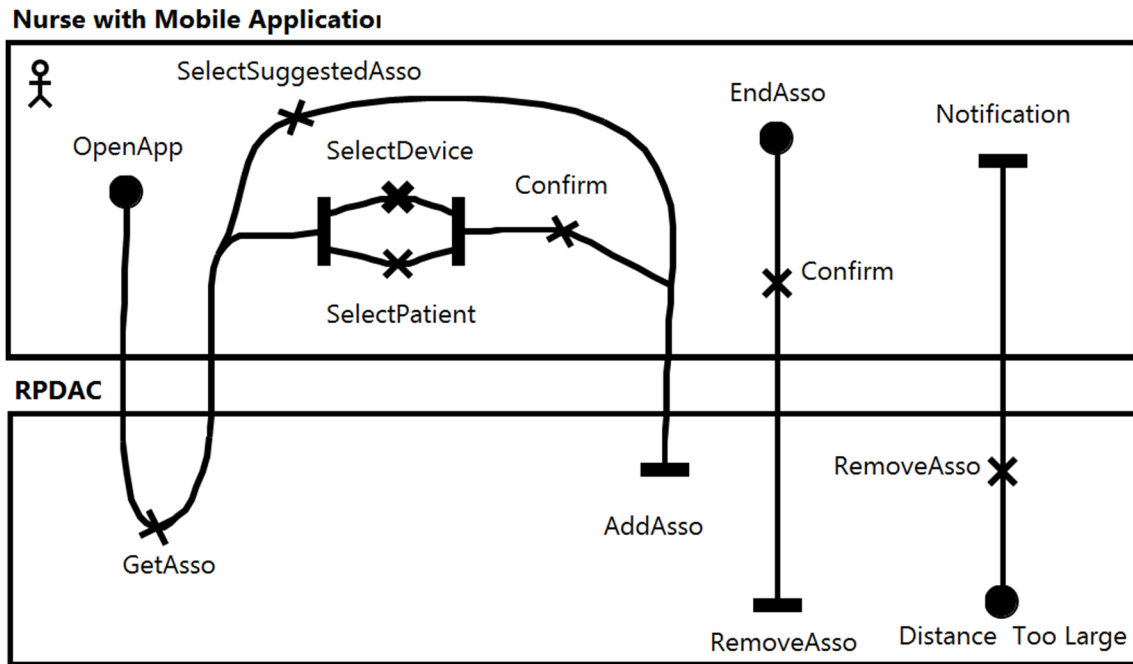


Figure 25. RPDAD General Scenarios

- Scenario 1:** The provider enters the room and goes to the right of bed1, starts the application, accepts the suggestion from the system (which shows the patient in bed1 and the closest device) enabling an association between the provider, the patient and the device, checks the list of associations, and does a manual disassociation of this recently-added association with the tablet application.
- Scenario 2:** The provider, still next to bed1, opens the application but now rejects the suggestion. He selects another patient (in bed2) and another device in the room and associates them. The patient in bed2 goes to the corridor with the device (no alert) and comes back without it (the patient-device distance is

now too large). The associated provider gets a disassociation alert, and removes it from the alert tab in the tablet application.

In this demonstration, the only person interacting with the RPDAD system is the nurse, via a (Samsung) tablet running our Android application. Figure 25 describes, with a simple Use Case Map model, the four main scenario parts tested in the application (accept and reject the association on the left, manual disassociation in the middle, and automatic disassociation on the right). Figure 26 provides partial snapshots of the graphical user interface on the tablet. When opening the application (OpenApp in Figure 25), the nurse is automatically identified (through RTLS by her badge) and the patient and device closest to her will be suggested right away as a potential association, to avoid wasting time (Figure 26 left).

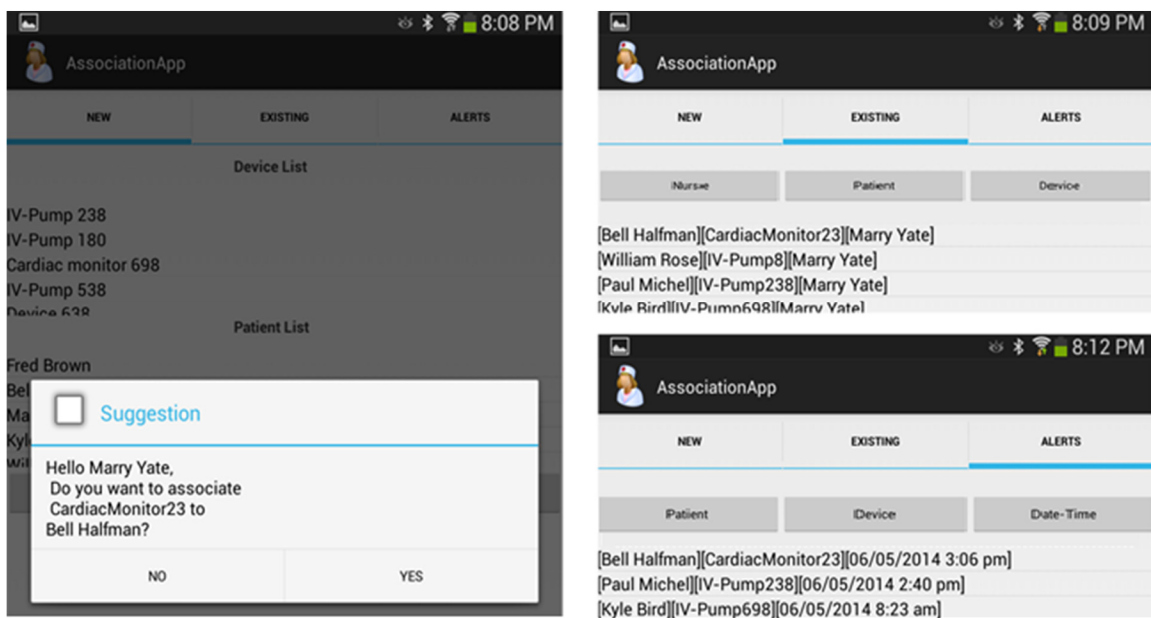


Figure 26. Android Tablet Application: New Association (Left), Existing Associations (Top-Right), and Alerts Tabs (Bottom Right)

If she agrees with the suggestion, the association is created and added immediately, otherwise she can select a patient and a device from all options in the room (sorted by proximity), which are available in the first tab of the Android application, and then confirm.

The nurse can create many such associations for one patient, but only unassociated devices will be shown by the application (as one device can only serve one patient). At any time, the nurse can monitor existing associations with the second tab of the Android application (top-right of Figure 26). One association can be selected and ended manually (EndAsso in Figure 25), leading to a disassociation.

If the RPDAC server detects that the distance between a device and its associated patient becomes too large (DistanceTooLarge in Figure 25) according to a predefined maximum distance for this type of device (configurable in the system), then an automatic disassociation occurs and the nurse receives an alert, also listed in the third tab of the application (bottom right of Figure 26). Once this alert/notification is acknowledged, the record is moved to the *Old Disassociation* table. Overall, the two general scenarios (discussed in the scenario part) were completely covered during this demonstration. Although there were many difficulties and unexpected issues that came from the RTLS equipment, the system was able to support the demonstration and the bugs and errors detected were fixed later, before the more formal experimentation presented in the next section.

5.2. Experimentation

In this section, the experimentation framework for RPDAD is discussed. This section starts by defining the experiment's motivation, object, purpose, perspective, domain, and scope. Furthermore, the experiment planning is clarified in terms of test design, evaluation criteria, and measurements. Later on, the experiment operation is defined in terms of preparation and execution. The interpretation of the experimentation results is also presented. These framework phases are inspired from recommended experimentation roles described by Basili et al. [4].

5.2.1 Experiment Definition

At this point, it is best to recall the research hypothesis to better understand the goal of the experimentation and to justify the definition details.

Hypothesis: *The design of a software system that **monitors and tracks patients and their assigned devices** and manages their connectivity in **real time** is feasible in a way that provides **accurate location** in order to support **patient safety**.*

Experiment motivation: as discussed in the introduction, the general motivation for this research is to address challenges with non-automatic associations (e.g., barcoding systems) and disassociations, and the unknown location of required mobile medical devices (e.g., cardiac monitors), which both have a huge negative impact on patient safety. Our system should be assessed during the experimentation to evaluate and improve patient care quality and efficiency in terms of patient-device association and disassociation management.

Experiment object: the object of the study is the examination of the final software as a product/system as well as its development process (the main challenges that drove us to modify our software will be discussed separately in the next chapter).

Experiment purpose: inasmuch as the motivation for this study is about assessing the product/system to assure its quality and effectiveness, the purpose of the study also involves evaluating the successes and failures of the product during the experimentation.

Experiment perspective: in this experimentation, the developer's and user's perspectives are the most important.

Experiment domain: the project domains include a hospital environment as a real context (*vivo*), and a university laboratory as an isolated and controlled experimental environment (*vitro*) [5]. The experiment done at the hospital (TOH) was included mainly for demonstration and validation purpose, and the experiment done in the laboratory was designed for the system evaluation.

Experiment scoping: clearly, the experiment scope is a single project, but with replication of the designed association/disassociation scenarios (scenarios 1 and 2 from section

5.1.2, executed 30 times each), over Wi-Fi with and without infrared beacons (leading to a total of 120 executions).

5.2.2 Experiment Planning

The second phase of the experimental process includes i) design details that fit the experiment scope, ii) criteria based on the experiment motivations and purposes that satisfy most of the specified requirements (discussed in Chapter 3), and iii) measurements based on the data collection.

Design: scenarios 1 and 2 can be run in different ways according to their use of different tags (asset tags, patient tags, or nurse badges) and their network connectivity (Wi-Fi with or without infrared with beacons). The system will be examined 120 times along four categories (Tag type-oriented over Wi-Fi, 30 times; Tag type-independent over Wi-Fi, 30 times; Tag type-oriented over Wi-Fi + infrared, 30 times; and Tag type-independent over Wi-Fi + infrared, 10 times per type of tag) to evaluate the effects of the network conditions and of the tag types. *Tag type-oriented* means that the right type of tag is given to the right role (e.g., assets with A4 asset tags) whereas *Tag type-independent* means that any tag is given to any role (e.g., patients with A4 asset tags), except in the last of the four categories, where every role had the same type of tag. The reason why the tag types are involved in the experimentation is that there were different issues and challenges faced during the demonstration at TOH that had a huge impact on the system performance. First, the Ekahau equipment used in the experiment was from an old generation (2009, although it was acquired in 2012), except for A4 asset tags (medical device tags) recently acquired by TOH, which ended up being almost incompatible with the Ekahau software and hardware. For instance, our Ekahau LB1 location beacons (the generation preceding the current LP2 beacons⁶) were completely useless for new A4 asset tags, in terms of accuracy and even of battery utilization. In addition, network coverage and signal strength were weak at TOH because of signal noise from existing networks and other equipment. Hence, the design of the experiment is partly based on lessons learnt during

⁶ <http://www.ekahau.com/real-time-location-system/technology/wi-fi-tags#!location-beacons-2>

the development process and prior demonstrations. The design also attempts to mitigate the quality issues with tag types through *Tag type-oriented* and *Tag type-independent* experiments.

Criteria: in this study, the product/system is examined via software quality factors while considering weaknesses and strengths of the available hardware. The criteria are also created based on the developer and user perspectives. In addition, covering all system requirements from Table 10 is an important evaluation criterion. This leads to the following five categories of criteria:

- **Functionality:** During functional testing, many attempts have been made to verify that the system works correctly according to its requirements. Evaluating location accuracy is very important here as accuracy is key to the success of this system. During the experimentation, the location accuracy has been evaluated in each run by comparing the real location of all tags to the Ekahau Vision map and the reported distance in RPDAD application (see Figure 31 and Figure 32).
- **Reliability:** In the demonstrations, we strove to maintain the system stable at a specific level of performance, especially when some unexpected conditions happened. Consequently, reliability of the system became important and this has been evaluated in terms of fault tolerance and robustness. To evaluate the tolerance to faults in the system, if the RTLS equipment (hardware) or the network does not work well, the system (in this case, the Android mobile application connected directly to the RPDAD server) shall still be working without crashing. In practice, this means the application should not stop working while there is no location accuracy provided by the available network and available tags. The system has been controlled by suitable notifications that guide a user while the network does not work well. Moreover, in the worst case scenario, manual association and disassociation can be run without any difficulties and this shows the system is working well logically. For robustness, the system is deemed robust when the database is faced with unexpected queries or when transferring data through sockets between the Android appli-

cation and the RPDAD server is impossible. Therefore, the more possible failures have been considered during the development process, the higher the system's level of robustness and fault tolerance.

- **Efficiency:** time efficiency needs to be measured to check appropriate response and processing times. In this study, the average durations spent handling association suggestions, manual associations, and manual disassociations have been measured. However, the time spent handling automatic disassociations is completely dependent on the defined RPDAD configuration setting. This configuration can define the frequency at which disassociation conditions are checked.
- **Precision:** one major advantage of this system is the automatic suggestion of an association that recognizes the patient and device closest to the nurse who wants to associate a patient with a device. Therefore, this suggestion shall be as precise as possible for the nurse to make a proper decision. As a result, this criterion identifies the true positive rate of association suggestions. Furthermore, in terms of disassociations, a confusion matrix has been used to measure recall and precision.
- **Usability:** for this criterion, the only factor that is assessed here is the usability of the Android application. Therefore, the usability and operability of the application have been checked during the development to assure that the application is easy to understand, use, and control from the user's perspective. However, a formal usability study (involving real nurses) is outside the scope of this thesis.

Measurements: in this part, the characteristics of the system that can provide significant information to cover quantifiable criteria have been identified and measured. As a result, some critical attributes that have a huge impact on accepting this product as a real-time, location-based, patient-device association and disassociation system have been measured, such as response time to check the real-time attributes of the system, location accuracy to judge the location-based reliability, the percentage of true association suggestions to

check the feasibility of a fast association process, and disassociation performance to validate one of the main capabilities of the system.

Accordingly, in each scenario run, the time of the association process, in terms of receiving a suggestion, and the time needed to detect disassociations automatically have been measured to evaluate the real-time performance. It has to be mentioned that measuring the entire time needed to complete the association scenario depends on the nurse movements, while measuring the time for automatic disassociations depends on the RTLS configuration settings defined in the RPDAD server.

The starting point for the association time is the activation of the Android application to receive a suggestion. Generally, the association process done by a nurse can be predicted as well, but by considering that the nurse knows already the name of the patient and the device. For the automatic disassociation, the checking period for existing associations in the configuration settings is defined as 12000 ($2*60*100$) milliseconds, which amounts to 0.2 minute. In other words, each 0.2 minute, the distances for all existing P2D associations are checked to detect and report one or many disassociations. Furthermore, for evaluating the location accuracy in each scenario run, the real positions of tags (device, patient, nurse) were compared with their positions on the Ekahau Vision tool and with their X and Y coordinates received via API commands from the RTLS. Therefore, a Boolean result for each run has been used, and at the end, the percentage of correctly reported tag locations was calculated.

Another important factor that was mentioned before is the precision of association suggestions. A Boolean result was again used for answering this question: Are the suggested patient and device the options closest to the nurse? Actually, by answering this question, the number of true positive and false positive cases can be clarified to calculate the precision rate. The last measurement is specified for the automatic disassociation performance by calculating the F-score, which is the harmonic mean of precision and recall. Consequently, a confusion matrix (TP: true positive, FP: false positive, TN: true negative, and FN: false negative) was used for the performance of the disassociation process and to calculate the following four metrics:

- $precision = TP / (TP + FP)$
- $recall = TP / (TP + FN)$

- $balanced\ accuracy = (precision + recall) / 2$
- $f\text{-measure} = precision \times recall / balanced\ accuracy$

5.2.3 Experiment Operation

This third phase of the experimental process consists in the preparation, execution and analysis [4]. In this part, the two scenarios that were run at the hospital are considered for experimentation as well.

Preparation: software and hardware configuration has been applied to provide a suitable environment for the execution step. A laboratory at the University of Ottawa has been equipped with all necessary hardware to simulate a room similar to the one used previously at the hospital for a demonstration. First, a private Wi-Fi network composed of a router and two access points (for triangulation) was set up. Three LB1 Ekahau beacons were installed for the Wi-Fi+infrared execution model, one beacon in the corridor and one at the head of each bed (Figure 27).

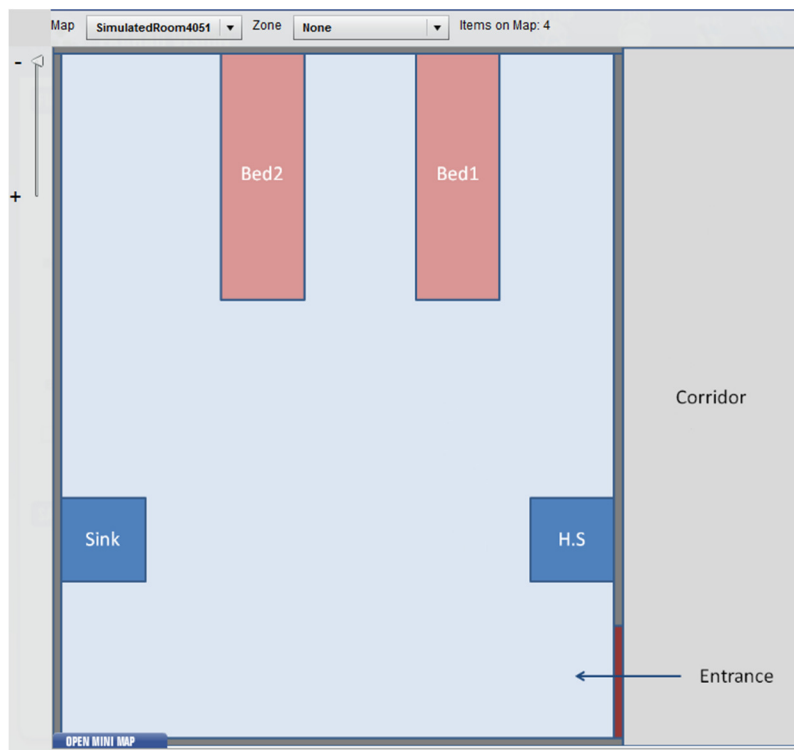


Figure 27. Patient Room Simulated in our Laboratory

Three RTLS applications were configured to communicate with the tags (Figure 28): Ekahau Site Survey, Ekahau Tag Activator, and Ekahau Controller. To use Ekahau Site Survey, the map of the room should be uploaded, and then the location of the access points and beacons should be identified on the map. Also, zones need to be identified for beacons. Having some surveys done with this software can help achieving accurate positioning of tags. The Ekahau Tag Activator software can be activated by a specific network card, and each type of tags has its own way of being activated. As soon as tags get activated, they can appear on the Ekahau Controller for further configuration. However, prior to this, the simulated map made with Ekahau Site Survey should be uploaded on the Ekahau Controller.

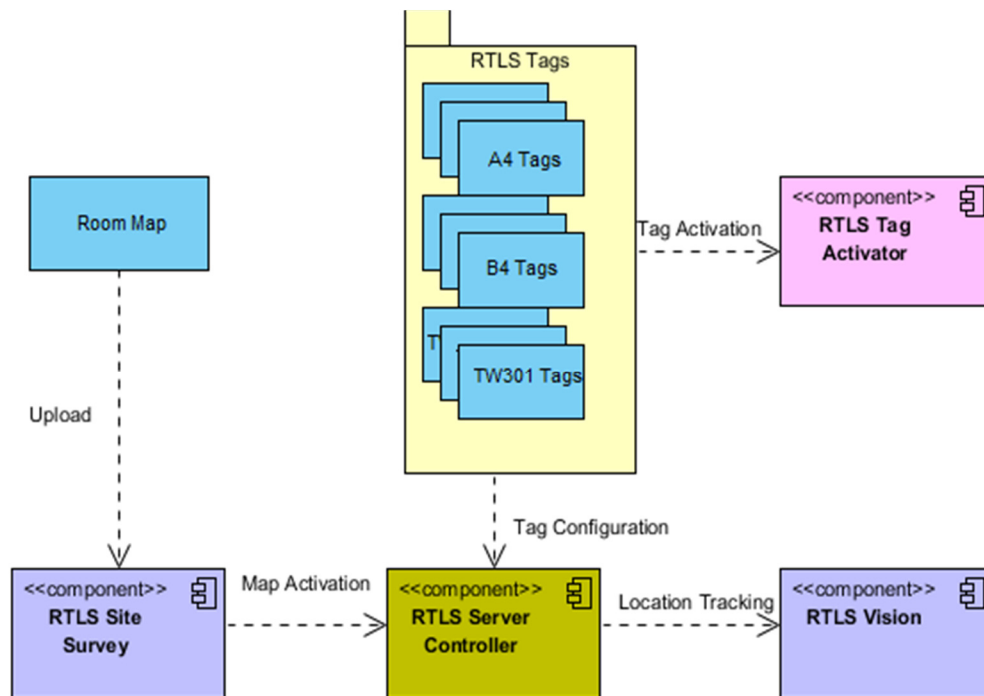


Figure 28. Ekahau Package and Applications

Finally, tags should be defined in the RPDAD database, more specifically in the Device table (Figure 16). It should also be noted that the name and MAC identifier of each tag must be exactly as in the Controller, otherwise tags cannot be processed while running the system. In other words, the RPDAD server can only recognize the tags that are defined in its database. At this point, the system is ready to be used for the execution step.

Execution: as discussed in section 5.1.2, we use two scenarios that combine two ways of supporting patient-device association (accepting the suggestion, rejecting the suggestion and selecting from device list and patient list) with two ways of supporting disassociations (manual, automatic). These scenarios have been run for two types of network environments (Wi-Fi or Wi-Fi+infrared) and two types of tag usage models (Tag type-oriented, Tag type-independent).

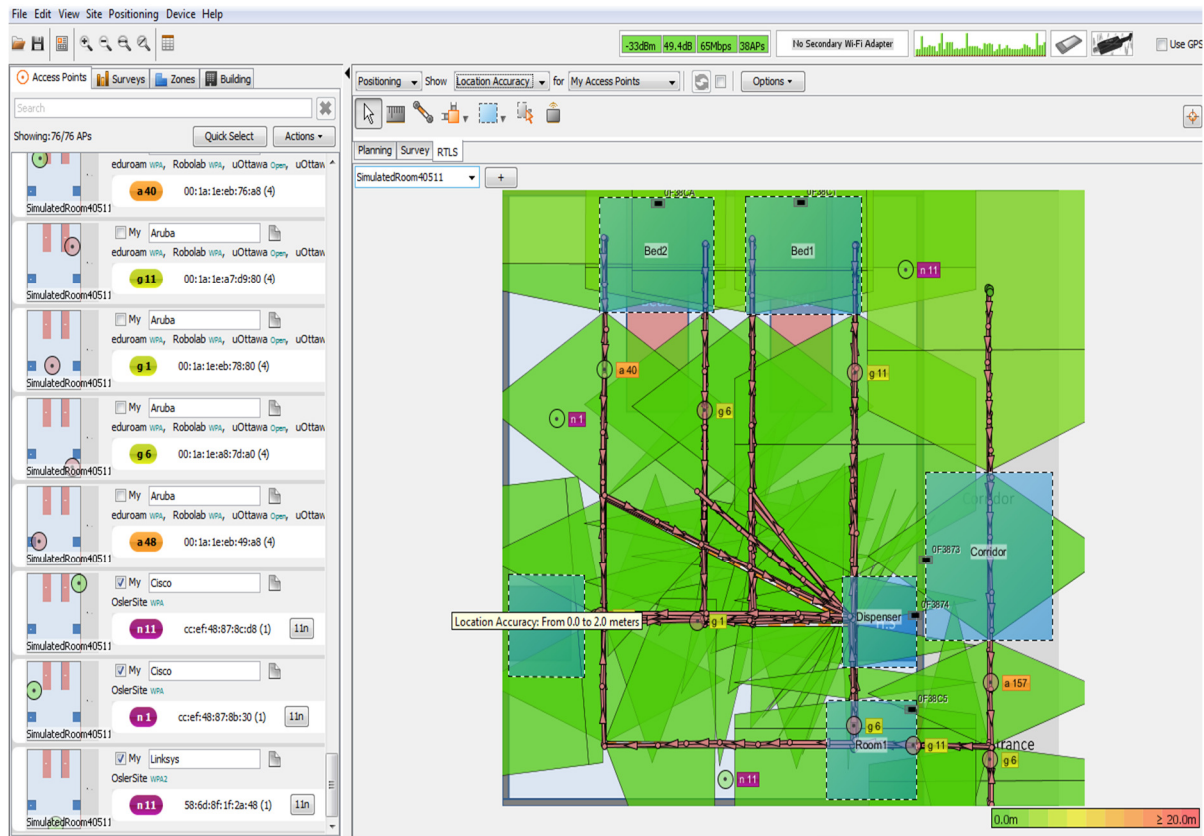


Figure 29. Site Survey Map with Beacons

The main reason for choosing two types of network environments was to evaluate the system functionality in terms of location accuracy, which has a huge impact on recall and precision metrics. We executed the system once after installing three beacons and two access points and a router for testing the system under Wi-Fi network and infrared signals. As discussed in the preparation part, all access points and beacons should not only be defined on the map (Figure 29), but they should also be installed in the room. After testing this network condition, all beacons should be removed from the map and room to

test the system under the other condition, which is working just with the Wi-Fi network, without beacons (Figure 30).

Due to many challenges faced during the implementation and experimentation phases with a Tag type-oriented approach (using each tag type just for its predefined usage), adding the Tag type-independent approach was the only way to evaluate the efficiency and logic of the system itself, especially when some tags are not behaving very well. For testing with the Tag type-independent approach over Wi-Fi and infrared beacons, the system execution was divided into three test sub-models; 10 times where the system has been run with just T301W tags (for all objects), 10 times for nurse badges (B4), and 10 times for asset tags (A4).

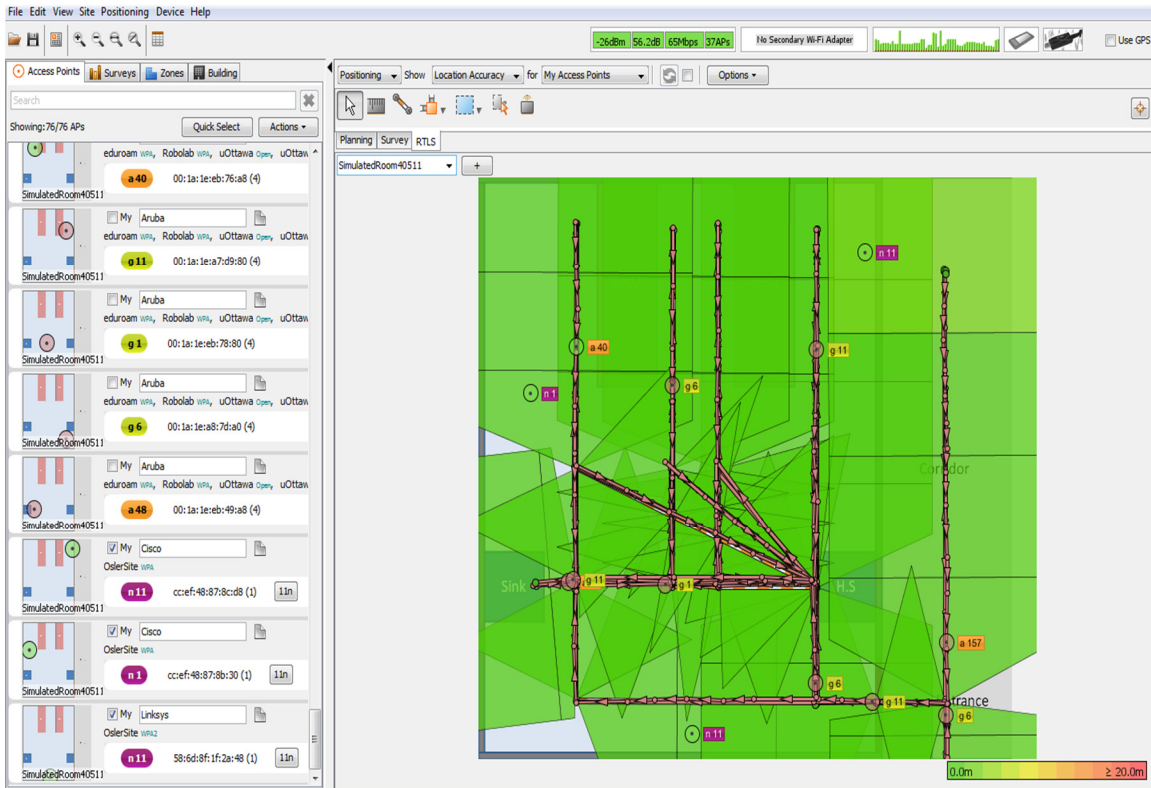


Figure 30. Site Survey Map without Beacons

Analysis: after executing 4 configurations 30 times each ($n=30$), the required data was collected. Table 12 shows, for each configuration, the minimum and maximum time spent for both activities (association and disassociation). Also, the real location of tags were observed and compared with Ekahau Vision and the RPDAD server, and the percentage of accurately reported locations was calculated.

Furthermore, since reporting unexpected disassociations is one of the benefits of the system, recall, precision and (for a more integrated evaluation) balanced accuracy and F-score metrics have been calculated. Additionally, the percentage of true-positive association suggestions has been reported to make the evaluation more complete, especially as we deal with four different configurations.

Table 12 Experimentation Results (n=30 for Each of the Four Configurations)

		Real-time performance				Location accuracy		Automatic disassociation				Asso suggestion
		Asso		Disa		Asso	Disso-ciation	Recall	Precision	Balanced accuracy	F-score	True positives
		Min	Max	Min	Max							
Tag type-oriented over Wi-Fi		2 s	7 s	3 s	55 s	35 %	25 %	90%	33%	61%	0.48	36%
Tag type independent over Wi-Fi		2 s	5 s	3 s	12 s	38 %	43 %	72%	59%	65%	0.64	46%
Tag type-oriented over Wi-Fi + infrared		2 s	5 s	5 s	66 s	72 %	69 %	90%	71%	80%	0.80	70%
Tag type-independent over Wi-Fi + infrared	T301W (n=10)	2 s	3 s	2 s	20 s	90 %	90 %	90%	100 %	95%	0.95	100%
	B4 (n=10)	2 s	3 s	5 s	56 s	80 %	90 %	90%	100 %	95%	0.95	90%
	A4 (n=10)	-	-	15 s	2 m	0%	0%	30%	100 %	65%	0.46	0%

Over Wi-Fi only: As shown in Table 12, using only Wi-Fi as a network environment for implementing this system is not sufficient since the F-score and balanced accuracy results (test accuracy measurement) and location accuracy, in the first two configurations, are low, especially when compared to the other configurations. In terms of time, if the tags' location could be recognized and synchronized in real time, these configurations would perhaps be as fast as the other ones. It has to be mentioned that, although all tag configurations here were modified to disable location beacon sensors, this did not have any impact on location accuracy. As shown in Figure 31 and Figure 32, the reported locations of tags are not their real locations. Also, the percentage of true association suggestions in these first two configurations shows that this approach is not reliable at all as a location-based real-time system. Finally, the reason why the Tag type-independent approach of-

fers better results than the Tag type-oriented one is because of the use of T301W tags instead of incompatible A4 asset tags.

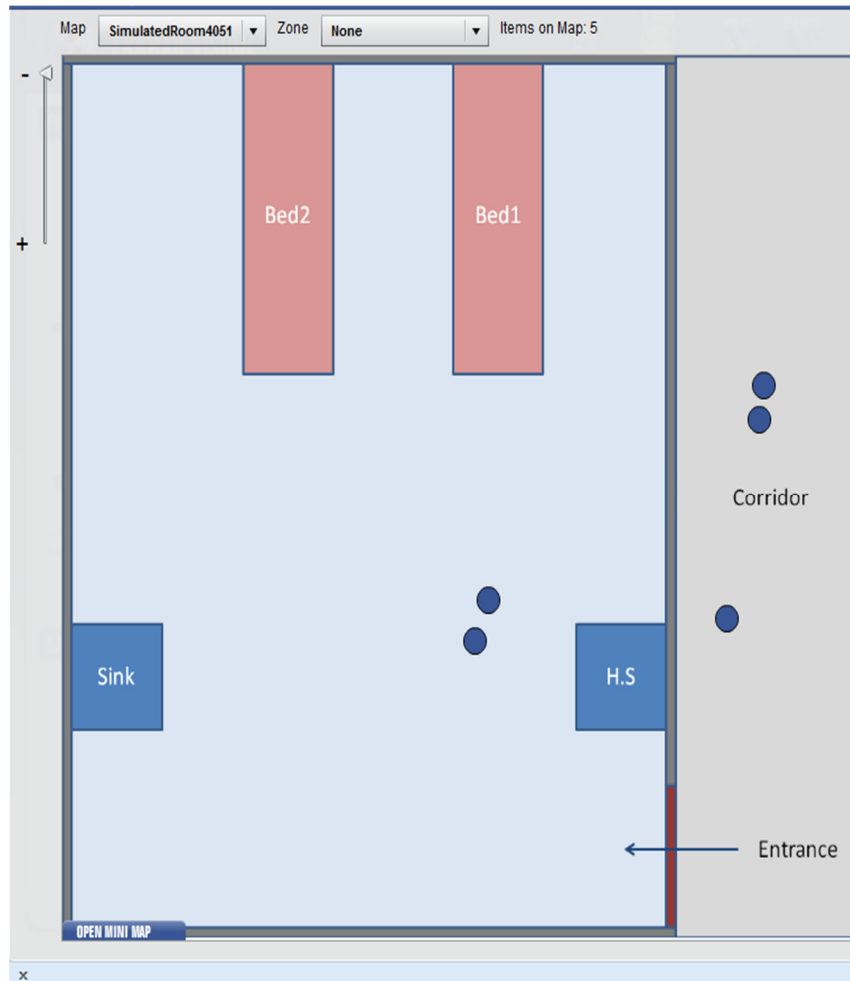


Figure 31. Ekahau Vision Snapshot for Tag Type-Independent over Wi-Fi

A4 tags only: As discussed before, another misbehaving configuration is when we are executing the system only with asset tags (last row in Table 12). There was not even a single true association suggestion received, and most of the received messages reported that the Android application was opened outside of the RTLS environment. Also, this option has the weakest F-score in the Wi-Fi+infrared configurations. This configuration was executed to confirm that the new asset tags were not compatible enough with the older RTLS equipment. Therefore, asset tags have been used just for the Tag type-oriented ap-

proaches, and clearly as it can be seen in the third configuration, their usage had a huge negative impact.

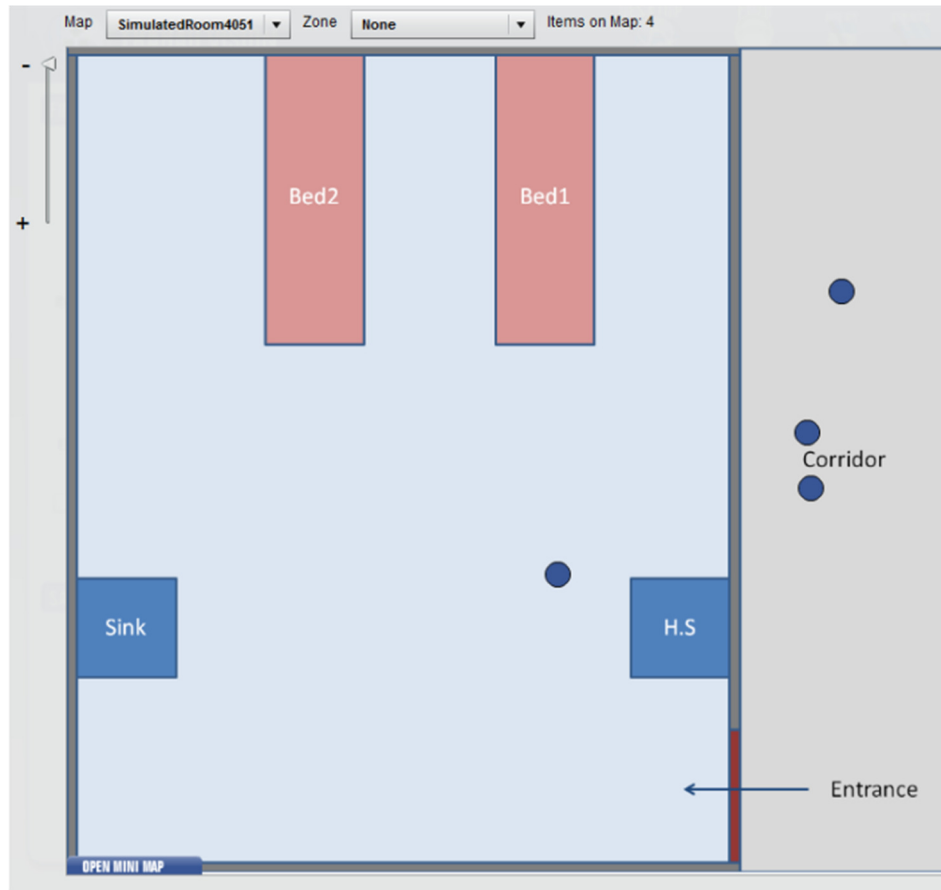


Figure 32. Ekahau Vision Snapshot of Tags' Type-Oriented over Wi-Fi

Tag type- independent over infrared and Wi-Fi: the system has been tested by just one type tag for each object (device, nurse, patient) to examine the functionality of the entire system, especially when we use the most accurate tags. When only T301W (patient) tags are used for the system, the results are excellent. 100% true association suggestions means the system is reliable for tag location recognition. 95% for F-score suggests the system can almost recognize all patient-device disassociations, especially when location accuracy becomes 100%. The system acts similarly when B4 tags (nurse badges) are used, but this option has less location accuracy. In these two cases, the system works very fast, for example the maximum time spent for disassociation detection when T301W tags are use is just 20 seconds.

Overall, all configurations have no major problem for manual disassociation and for selecting a patient and a device for association. This means the system never crashed down, and in the worst-case scenario (when the RTLS is down), the system is still usable for manual associations and for manual disassociations. System fault tolerance is high because the system can work at least in a lower service quality level without failing completely.

5.2.4 Interpretation

A remaining challenging part in the experimentation phase is decision making, that is, deciding whether or not a software product can be reliable enough to be used. One important aspect of the experimentation phase hence is the interpretation. It has to be determined from the analysis whether the hypothesis can be rejected or accepted [4]. Therefore, it is necessary to review the hypothesis one last time (the highlight words will be assessed):

Hypothesis: *The design of a software system that **monitors and tracks patients and their assigned devices** and manages their connectivity in **real time** is feasible in a way that provides **accurate location** in order to support **patient safety**.*

As discussed many times, the most interesting advantage of the RPDAD system is reporting patient-device disassociations, which can prove the system's ability to monitor and track patients and devices in real time. As observed in the experimentation, the worst configuration was using only asset tags (with a 0.46 F-score) or using all tags but over Wi-Fi. However, if there is no obstacle in location recognition and if all tags are working as accurately as patient tags (T301W), this system would be reliable at 95% in terms of tracking patients and devices in real time. Similarly, for suggesting the closest patient and device to the nurse, the system can be 100% capable of recognizing the accurate location of tags at the condition that tags behave accurately.

5.3. Chapter Summary

This chapter has discussed the validation of the RPDAD prototype through two deployments (in different buildings) and a more formal in-lab experiment. It also described many challenges encountered during the deployment at The Ottawa Hospital. The experimentation steps, including criteria and measures, were discussed. The experimentation operation took place in a simulated hospital room located in a laboratory of the University of Ottawa, and many system configurations with two possible scenarios have been evaluated. The results suggest that the logic of the application is valid, and that when working tags are provided, the system provides a good level of performance, accuracy, and robustness.

The next chapter discusses closely-related approaches and compares them with our solution. Threats and limitations of the system will also be discussed.

Chapter 6. Comparison and Evaluation

In this chapter, the main advantages and disadvantages of the RPDAD system are evaluated and compared with closely-related approaches. Limitations and threats to validity are also discussed.

6.1. Comparison

According to the data comparison and analysis part (Chapter 3) and the problem description (section 1.2), it is suggested to have two comparisons for the final evaluation: one that targets the server side, and one that targets the client side (mobile application). A short comparison with currently available methods is also provided.

6.1.1 Comparison with Server-Side Related Work

In section 3.2, four existing and closely-related approaches were highlighted to compare their strengths and weaknesses with the one developed in this thesis. Also, tracking objects in real time in each approach is a key factor for decision making. Table 13 (extracted from Table 4 and supplemented by a RPDAD row and a notification column) highlights the comparison of our work with these four approaches.

Table 13 Server-Side Related Work Comparison

	Real time Tracking	Association	Disassociation	Disassociation Notification
P7 [21]	YES	YES	NO	NO
P8 [46]	YES	YES	NO	NO
P10 [29]	NO	YES	Manual	NO
P11 [22]	YES	YES	NO	NO
RPDAD	YES	YES	Automatic	YES

The main and unique feature of our system is tracking patients and their assigned devices in real time to make the nurse becomes aware of any disassociation, whereas P7, P8, and P11 have real time object tracking, but not for supporting automatic disassociations. On the other hand, these systems monitor the medicine supply to inform the nurse, which is not done in RPDAD. Also, despite not working over Wi-Fi, P10 can manage a manual disassociation. Another interesting feature of RPDAD is for associating the right device with the right patient, and these related approaches have this option as well. However, as discussed in the experimentation part (Chapter 5), it is possible that RPDAD offers a non-optimal association suggestion to help the nurse in finding patients and devices automatically, which means that, due to a lack of equipment accuracy, the system does not recognize at 100% the options closest to a nurse while she is coming into a room. On the other hand, no other system covers this option.

6.1.2 Comparison with Client-Side Related Work

In section 3.3, five existing approaches were highlighted in Table 7 and Table 8 to compare their strengths and weaknesses with the mobile Android application developed in this thesis. To be synchronized with the server side, tracking objects in real time as a feature for mobile applications is a must for making a decision regarding our research hypothesis. Furthermore, as association recording, disassociation in real-time, and disassociation notifications are important aspects of a desired solution, these criteria are also used. Table 14 compares our work with the five most closely-related approaches.

Table 14 Client-Side Related Work Comparison

	Activator	Real time Tracking	Associa-tion	Disasso-ciation	Notification
PBM3 [59]	Patient	YES	NO	NO	YES
PBM7 [55]	Patient	YES	NO	NO	YES
HPBM1 [13]	Nurse	YES	NO	NO	NO
HPBM5 [37]	Health Provider	YES	NO	YES	YES
HPBM6 [50]	Physician	YES	NO	NO	NO
RPDAD Client	Health Provider	YES	YES	YES	YES

The first two systems are handled with the patient’s help, which is different from our client application. However, all mentioned client applications are tracking and monitoring objects, especially patients. Still, no related client-side system is tracking patients with their associated devices. Also, there is no coverage of any association and disassociation features in any client-side applications, except for HBPM5 which covers utilization of mobile device resources. In terms of notifying health providers to check the status of patients, not only in the disassociation case, PBM1, PBM7, and HBPM5 have notification capabilities, just like our client application.

6.1.3 Comparison with Currently Available Methods

One of the objectives of developing the system in this thesis is to compete with barcoding systems, which is the common approach currently used for associations in many healthcare organizations. In this section, the main advantages and disadvantages of these two systems are evaluated and compared. It is however very difficult to compare them quantitatively, especially in terms of time and accuracy. Before starting the development of RPDAD, we observed and shadowed nurses using barcoding at TOH to find out how fast and accurate can be this approach. For example, recording spent time for any association (mostly patient-to-medication associations) was not always possible because of interruptions or some difficulties that some nurses had during associations. Therefore, in this part, we are trying to compare the RPDAD system with barcoding systems qualitatively. Table 15 summarizes this discussion.

Table 15 Comparison with Main Current Method: Barcoding

	Misidentification	Real-time Tracking	Asso.	Disasso.	Battery/ Network Issues	Medicine Supply
Bar-coding	MORE	NO	YES	NO	NO	YES
RPDAD	LESS	YES	YES	YES	YES	NO

Ideally, the Barcode Medication Administration Systems (BCMAs) should confirm the five “rights” of medication administration: right patient, drug, dose, route, and time (advantages) [36]. However, 31 probable problem causes were identified during BCMAs’

workarounds, such as unreadable medication barcodes, malfunctioning scanners, unreadable or missing patient identification wristbands, non-barcoded medications, failing batteries, uncertain wireless connectivity, etc. Therefore, consequences of these errors are incorrect administration of medications, wrong doses, wrong times, and wrong formulations (disadvantages) [36]. Comparing this to our system, in the context of the association, the barcoding system has a complete association for patients (medicine supply, medical devices, etc.), whereas RPDAD system has just P2D associations. In contrast however, barcoding cannot manage any disassociation while RPDAD can. Additionally, there is no misidentification for patients and devices because they are equipped with tags (advantage), not barcode that may be unreadable because they get cut, smudged, or chewed. Moreover, as we observed in the experimentation phase, there are some disadvantages of RPDAD, such as failing batteries and uncertain wireless connectivity, which cause the reporting of incorrect location by the RTLS and consequently incorrect disassociation or association suggestions.

6.1.4 Conclusion

Despite all the difficulties that happened during RPDAD's implementation and validation, as seen in Chapter 5, RPDAD can be a strong competitor to barcoding systems and all selected related approaches, with many original benefits. One condition however is that RTLS technology keeps improving, in terms of accuracy, functionality, and energy consumption.

6.2. Limitations and Threats to Validity

Three types of threat to validity are addressed here, as suggested by Perry et al. [47]:

- Construct validity: determines how the system actually answers the research hypothesis.
- Internal validity: examines any bias and other confounding factors.
- External validity: verifies how much our results can be generalized.

6.2.1 Construct Validity

As specified in our hypothesis, entirely supporting patient safety is the most important objective, but the experimentation results are not sufficient to prove this claim. Clearly, one threat to construct validity for our study is having different results in terms of accuracy, for example with balanced accuracy between 61% and 95%, we cannot rely on the reported accuracy unless RTLS technology improves substantially. As shown in Table 12, we can have 95% true disassociation reports and even 100% true association suggestions at the condition that RTLS technology meets all necessary requirements, because our system, basically, has no apparent problem in terms of functionality. Therefore, we still need to wait for RTLS technology improvements to test the RPDAD system properly, in the hospital, and to validate the results again.

6.2.2 Internal Validity

The Ekahau RTLS equipment and software available in our laboratory are outdated and need to be updated, which affected the performance of RPDAD as the hardware stopped working suddenly and the software did not respond at times. Furthermore, RPDAD was validated and evaluated just by the thesis author and an assistant (volunteer), which may introduce several levels of bias.

6.2.3 External Validity

The RPDAD system could not be validated at TOH because the given room was no longer available by the time we were ready to perform the experimentation. Therefore, RPDAD was only studied in the simulated room at the University of Ottawa. It is not guaranteed that the results observed in the thesis would be the same at TOH or at another healthcare organization. We cannot yet generalize our work until it is validated several times in hospitals (using different networks, floors, people, times of day, etc.), not only as a prototype, but also as a complete system (pilot). In addition, whether the existing solution would be acceptable by nurses from a privacy perspective remains a research question.

6.3. Chapter Summary

This chapter summarized the comparison with closely-related approaches and current methods to evaluate our contribution to the problem's resolution. Various threats to validity have also been identified. In the next chapter, we will conclude the thesis and identify future work items.

Chapter 7. Conclusions and Future Work

This chapter recalls the main contributions of this thesis, and enumerates specific items for future work inspired from limitations and threats observed in the previous chapters.

7.1. Contributions

In our system, we examined the potential use of an existing RTLS to improve patient safety in terms of having correct creation and deletion of patient-device associations, in real time and with minimal effort. By integrating RTLS technology, an RPDAD server, and a mobile Android application, we demonstrated the feasibility of monitoring and controlling associations between a patient, medical equipment, and a healthcare provider. Generally, this work has contributed the design and a prototype of a real-time tracking system for patient and device association and disassociation by using RTLS technology, with the following functionalities spread over the server and the mobile client:

1. Control and monitor association between a patient, (mobile) medical equipment, and provider (nurse).
2. Provide a simple tool for providers to find the nearest available medical devices.
3. Suggest the best and closest option (among all patients and devices in the room) to a provider (nurse) to efficiently create a P2D association.
4. Track automatically patients with associated devices (e.g., IV pumps, cardiac monitors, vital sign monitors) in real time.
5. Detect an (unexpected) disassociation between the patient and the device in real time, and notify the responsible nurse.
6. Implement a prototype for The Ottawa Hospital and consider important scenarios that can happen in this case to support and demonstrate the importance of tracking associations and disassociations.

The validation and experiments done in this thesis provide much evidence in support of the research hypothesis. Although there is room for improvement, the RPDAD system compares advantageously with related work and, to some extent, with currently used approaches such as barcoding systems.

7.2. Future Work

Our approach goes beyond existing solutions by handling automated disassociations, and likely at a lower cost by reusing existing infrastructures (e.g., in the context of an RTLS acquired for asset management and/or care flows). For future work, in addition to more extensive validation (discussed in Chapter 5, especially in real environment with the latest equipment), we observe many research and development opportunities:

- Improve and assess the usability of the tablet application’s user interface, especially with the addition of a visual floor/room map for precise equipment localization. Such a feature would help support nurses in situations where the mobile equipment is located outside the patient room.
- Improve the location accuracy by enhancing the network, e.g., by studying the accuracy gained by adding more beacons or routers, or by integrating newer technologies where it makes sense, such as long-range RFID tags [8].
- Decouple the RPDAD application server from the underlying Ekahau-based API. Having an intermediate API would allow the server to interact with other location-based technologies (RTLS-based or not). One serious option here would be to use Part 1 of the ISO/IEC 24730 standard. This standard defines an API for RTLS that targets asset management and other services in a way that promotes interoperability between RTLS products [33]. However, even if the first version of this standard was released in 2006 with a revision in 2014, there is no clear evidence that Ekahau supports ISO/IEC 24730-1 at this time.
- Provide a solution to notify nurses of the lack of medicine supply in some medical devices (e.g., IV pump), e.g., by integrating this system with barcoding systems.

- Adopt a business intelligence tool for creating reports from the association/disassociation database, and evaluate how best to integrate such system with existing hospital information systems.
- In the long term, a pilot study will be needed to assess the real impact of such system on the reduction of effort and errors in hospitals.

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