Low-power Wireless ECG Monitoring System for Android Devices

Sistema inalámbrico de bajo consumo para monitorización de electrocardiogramas desde dispositivos Android

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Abstract

People affected by specific cardiovascular diseases require of a constant monitoring of their vital signs, to which end specialized, high priced and big sized equipment is employed. Reduction of the energetic requirements and improvement of the portability are the objectives for the next generation of monitoring systems. This document presents the development of a low-power wireless ECG monitoring system for Android devices. By using the mobile phone or tablet of the user the total amount of needed devices is limited, and the application of the 802.15.4 wireless communication standard substantially decreases the energetic consumption when compared to wider spread ones like Bluetooth. The development of an USB 802.15.4 receiver device and the Android monitoring application results in a system targeting an operation as unintrusive as possible. Systems like this one have proved to be highly useful and a generalization of their employment is to be expected.

Keywords ECG, Android, MSP430, FreeRTOS, Shimmer, USB, 802.15.4

Las personas afectadas por ciertas enfermedades cardiovasculares requieren de una estrecha vigilancia de sus constantes vitales, lo cual supone el empleo de equipos especializados de elevado coste y tamaño. La reducción del consumo energético y el aumento de la portabilidad son los objetivos de la próxima generación de dispositivos de monitorización. En este documento se presenta el desarrollo de un sistema inalámbrico de monitorización electrocardiográfica portátil de bajo consumo para dispositivos Android. Al reutilizar el terminal del usuario se reduce el número de dispositivos necesarios, y la aplicación del estándar de comunicación inalámbrica 802.15.4 disminuye el consumo de energía de forma significativa respecto al uso de otras alternativas como Bluetooth, la más empleada en este ámbito. El desarrollo de un receptor USB 802.15.4 junto con la aplicación de monitorización para Android resulta en un sistema orientado a ser lo menos invasivo posible en la vida del usuario final. Sistemas de estas características han desmostrado ser de gran utilidad y se espera un uso generalizado de los mismos en casos de necesidad de monitorización constante.

Palabras clave ECG, Android, MSP430, FreeRTOS, Shimmer, USB, 802.15.4

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Pablo Fernández | Rafael de la Hoz | Miguel Márquez

To Carlos, for his mad soldering skills and wise guidance,
to Fran because of his healthy support,
and very special thanks to everyone that has been there,
bearing with us.

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Resumen en Español

En este documento se expone la investigación realizada con el objetivo de desarrollar un receptor del estándar de redes de área personal inalámbricas 802.15.4 del IEEE para dispositivos Android a través de USB, aplicado a un sistema completo de monitorización electrocardiográfica (ECG), así como el proceso de desarollo del mismo. Este sistema se enmarca en el ámbito de la atención sanitaria personal: su principal aplicación es la montorización del estado del corazón por parte de un particular, eliminando la dependencia, respecto a esta tarea específica, con los sistemas de atención sanitaria tradicionales.

Recientemente ha surgido un gran interés, tanto en el ámbito académico como en el industrial, en la producción de sistemas de monitorización ECG portátiles y de bajo consumo, llegando a ser una de las principales aplicaciones de las redes de sensores corporales inalámbricas.

Para maximizar la portabilidad, en el desarrollo de estos sistemas se han empezado a emplear dispositivos móviles de gran capacidad de cómputo, particularmente smartphones, debido a la gran difusion que han tenido en los últimos años. En el 2011 se presentó un sistema, colaboración entre la Universidad Complutense de Madrid (UCM) y la École Polytechnique Fédérale de Lausanne (EPFL), para monitorización ECG de ámbito personal empleando un iPhone como visualizador y Bluetooth como tecnología de comunicación inalámbrica.

De los resultados obtenidos por ese proyecto surge la presente iniciativa que trata de llevar al siguiente nivel las características inherentemente buenas de bajo consumo y bajo coste del mismo mediante la aplicación del protocolo 802.15.4, de mucho menor consumo energético que la tecnología Bluetooth, y la sustitución del dispositivo iOS por uno basado en Android, debido a su mayor accesibilidad y el menor coste, en general, de éstos.

El sistema desarrollado en este proyecto presenta al usuario una representación visual de su onda ECG en tiempo real, resaltando puntos relevantes para simplificar la compresión de los datos mostrados. También muestra información sobre el ritmo cardiaco, y toda esta información es almacenada de forma transparente al usuario para su posterior consulta.

Esta funcionalidad es posible gracias a la operación conjunta de los tres dispositivos que forman el sistema de monitorización: el nodo de delineación ECG, el receptor 802.15.4 y el dipositivo Android que actúa de interfaz con el sistema. El nodo de delineación ECG va conectado a la red de sensores corporal del usuario y se encarga de la captura y posterior análisis de la onda ECG, así como de la codificación y envío de la misma de forma inalámbrica. El receptor 802.15.4 conectado al sistema Android a través de USB controla la recepción de datos a traves de dicho protocolo y el envío de la información recibida al dispositivo Android. Éste actúa como decodificador y visualizador en tiempo real, y, como interfaz con el sistema, gestiona las conexiones inalámbricas y almacena y muestra los datos recibidos.

Los objetivos del proyecto son, entonces, el desarrollo de la aplicación para dispositivos Android, la producción del receptor 802.15.4 y la comunicación de ambos con un nodo delineador ECG ya existente.

La aplicación para dispositivos Android, como ya se ha mencionado, es la interfaz con la que el usuario interactúa con el sistema. Su diseño sigue las prácticas comunes de aplicaciones para este sistema operativo ya que el objetivo es que la curva de aprendizaje sea, si no nula, muy suave. Los motivos para emplear Android como sistema operativo base son tres: la importancia de éste entre los sistemas operativos móviles, el mayor rango de precios de los terminales que lo soportan, que permite una mayor difusión del sistema debido a la existencia de dispositivos de precio más reducido, y la naturaleza libre y de código abierto del entorno de desarrollo, característica que facilita la posterior expansión del sistema. Todos estos motivos pueden resumirse en que el empleo de Android como sistema operativo permite el acceso de un mayor número de usuarios al mismo.

En cuanto al nodo delineador de la onda ECG, el objetivo es emplear uno ya desarrollado para el proyecto. Esto es así porque tanto el nodo delineador como la red de sensores corporales que capturan la onda ECG son sistemas especialmente complejos cuyos desarrollos ocuparían, cada uno, un proyecto de la envergadura del actual. Es más, el nodo empleado es el resultado de la colaboración de dos universidades europeas y una nod tesis doctoral.

El nodo delineador que se emplea en el proyecto es obtenido en el proyecto de la UCM y la EPFL antes mencionado. Este nodo se desarrolló inicialmente como un delineador de electrocardiografía en tiempo real de bajo consumo con capacidad para envíar los datos de forma inalámbrica a través de Bluetooth. En otro esfuerzo conjunto entre la EPFL y la UCM se dotó al nodo de funcionalidad para el envío empleando 802.15.4, pero tan sólo al nivel necesario para realizar algunas estimaciones de consumo. Incluso con la utilización real del estándar 802.15.4 estando aún por llegar, el nodo presenta las características necesarias para convertirse en un excelente punto de partida para el alcance de los objetivos del proyecto.

El componente más importante del sistema en cuanto a este proyecto se refiere es el receptor USB de 802.15.4 en tiempo real para dispositivos Android. Su desarrollo es una necesidad puesto que los dispositivos Android actualmente no proporcionan soporte para el protocolo 802.15.4, aunque sí para otros como Bluetooth o Wi-Fi. Considerando que en el nodo delineador que se toma como punto de partida para el sistema la operación que supone mayor consumo de batería es la utilización de la infraestructura Bluetooth, como confirman los estudios realizados por la UCM y la EPFL, la producción del receptor 802.15.4 es, pues, imperativa.

La existencia de otros proyectos con el objetivo de la dotación a dispositivos móviles del estándar 802.15.4 es un hecho conocido desde el inicio del proyecto, aunque éstos no tengan como objetivo el campo de la biomedicina o la monitorización personal. El motivo para no apoyar o emplear alguno de ellos es doble: por un lado, al comienzo del proyecto éstas iniciativas se encuentran o bien inconclusas o bien paralizadas; más aún, todas son proyectos aislados, generalmente desarrollados por una única persona y sin ningún tipo de soporte oficial ni garantías de finalización. Por otra parte, y siguiendo la idea de obtención de un sistema de tamaño reducido, el objetivo de este proyecto es emplear el dispositivo Android como maestro en la comunicación USB, de forma que el receptor 802.15.4 obtenga la alimentación a través de él, eliminando así la necesidad de emplear una batería que incrementaría el tamaño del receptor. Ninguno de los proyectos existentes emplea la capacidad de los dispositivos Android para asumir el rol de maestro en la comunicación, así que no son de utilidad real para el proyecto.

El desarrollo del proyecto viene motivado por dos razones principales: la potencial utilidad que demuestra tener un sistema de estas características y el interés que suscita a nivel académico.

Según la Organización Mundial de la Salud (OMS), las enfermedades cardiovasculares representan la principal causa de mortalidad a nivel mundial. Sin embargo, la vigilancia que requieren las personas afectadas no es asumible, por lo general, por los sistemas de sanidad tradicionales. La monitorización doméstica continua supondría una gran ayuda para estas personas, pero todavía se trata un objetivo a cumplir.

En un escenario como este, las redes inalámbricas de sensores corporales (wireless body sensor networks, WBSN) se presentan como herramientas de monitorización eficientes y asumibles económicamente. Particularmente, las WBSN aplicadas a la monitorización electrocardiográfica son de gran utilidad en el seguimiento de enfermedades cardiovasculares. De hecho, proyectos como el de la UCM y la EPFL mecionado anteriormente promueven la expansión de sistemas como estos.

Además, con el uso de dispositivos portátiles, en particular smartphones, para mostrar los resultados de la monitorización se persigue la expansión de estos sistemas en todos los ámbitos de la sociedad, ya que permiten integrar el sistema en dispositivos ampliamente utilizados, evitando así la necesidad de cargar con aparatos adicionales. La elección de Android como plataforma reponde a los factores de difusión y menor coste de los terminales que se mencionaron anteriormente, con el objetivo principal de maximizar la expansión del sistema.

Asimismo se busca el uso más extendido del sistema con el aumento de la duración de la batería y la reducción del tamaño de los nodos de monitorización: un consumo de batería menos exigente permite un número menor de interrupciones en la monitorización producidas durante el proceso de carga de la misma, mientras que el menor tamaño del dispositivo facilita el emleo contínuo del mismo. La utilización del estándar 802.15.4 responde a la búsqueda de la realización de estos objetivos.

En conjunto, el uso de un dispositivo Android con capacidad de recepción

802.15.4 en un sistema de monitorización electrocardiográfica continua rebaja los requisitos de consumo de batería y tamaño del sistema completo, y de esta forma mejora la posibilidad de ser transportado y relaja las restricciones en su aplicación.

Desde un punto de vista académico, la principal motivación que plantea el desarrollo de este proyecto es el hecho de que reune prácticamente todas las áreas de la carrera de Ingeniería Informática. Desde el mismo comienzo el proyecto implica desarrollo tanto software como hardware además de investigación en ámbitos externos al alcance de la propia carrera, como tecnologías inalámbricas de bajo consumo o desarrollo para dispositivos móviles, así como tareas de diseño y desarrollo en un amplio rango de niveles de abstracción.

Se espera también que las tecnologías basadas en la especificación del estándar 802.15.4 del IEEE como ZigBee verán incrementada su relevancia a medio plazo debido a sus potenciales aplicaciones en campos como la domótica y la biomedicina, entre otros.

Además, tanto el desarrollo de aplicaciones como de accesorios para smartphones u otro tipo de dispositivos portátiles son unas de las prácticas más habituales hoy en día en el ámbito del desarrollo de sistemas informáticos, y representan algunas de las actividades más demandadas. Por tanto, entrar en contacto con ellas proporciona una experiencia adicional en un campo puntero que no hace sino amplíar nuestro rango de habilidades y, por consiguiente, incrementa nuestro valor en el mercado laboral.

Al comienzo del proyecto, evaluando los objetivos, se decide hacer una distinción muy clara entre dos partes del proyecto: por un lado, el desarrollo de la aplicación para Android y por otro, la investigación orientada al posterior desarrollo del receptor 802.15.4 así como la correcta utilización del nodo delineador seleccionado incluyendo las modificaciones que hubiera que hacerle al mismo.

El desarrollo la aplicación Android se trata de un proyecto de desarrollo software de tamaño manejable cuyo mayor riesgo consiste en la falta de formación del equipo en el ámbito del desarrollo de aplicaciones para dispositivos móviles.

Por su parte, el desarrollo del receptor 802.15.4 implica un esfuerzo de investigación hardware importante, ya que la mayoría de los objetivos planteados ni siquiera se sabe si son alcanzables. Es más, el desarrollo de dispositivos electrónicos al nivel requerido por el proyecto queda fuera del alcance de la formación recibida. Todo esto provee a la parte de desarrollo e investigación sobre hardware de un nivel de incertidumbre, tanto en la posibilidad real de alcanzar los objetivos propuestos, como en la capacidad del equipo para llevarlos a cabo, muy superior al existente en el desarrollo software.

Esta situación propicia la división del proyecto en dos subproyectos a desarrollar de forma independiente pero teniendo en cuenta en todo momento la estrecha relación entre uno y otro. De esta forma en cada desarrollo se pueden aplicar las metodologías, técnicas y planificaciones más apropiadas para el tipo de trabajo concreto a realizar. Atendiendo a la estrecha dependencia entre los dos proyectos, y buscando evitar grandes descompensaciones entre ambos, se fija una planificación común a todo el proyecto de forma que ciertos hitos deben alcanzarse a la par en ambos desarrollos.

De esta forma se asegura que la funcionalidad producida por un proyecto se completa en el otro mientras se deja libertad para aplicar el enfoque que se considere más efectivo en cada proyecto durante los ciclos de desarrollo. Además, dada la incertidumbre asociada a la investigación hardware, los plazos temporales para los hitos se asumen como variables y se manejan planes de actuación en la planificación del proyecto de desarrollo software para que el trabajo no se vea detenido por los potenciales retrasos. Se considera, entonces, que el camino crítico del proyecto está definido por el proyecto de investigación y desarrollo hardware y el proyecto de desarrollo software debe adaptarse a sus necesidades. Aún y así en la planificación del primero no se dejan de tener en cuenta las posibles contingencias del desarrollo software.

La tecnología seleccionada para el desarrollo del proyecto es la siguiente:

- *El dispositivo móvil tipo tableta basado en Android* Motorola Xoom

  Escogido entre otros modelos de terminales que soportan Android por su capacidad para asumir el rol de maestro en la comunicación USB. Además, la capacidad del procesador que incorpora y el hecho de integrar una GPU lo hacen especialmente aplicable para la consecución del objetivo de mostrar los datos de la electrocardiografía en tiempo real.

- *Nodo delineador de ECG del proyecto de la UCM y la EPFL*

  Este nodo se basa en la plataforma inalámbrica de sensores corporales *Shimmer* para la captura de la onda electrocardiográfica y realiza un análisis de la misma (denominado delineación), enviando los datos a través de Bluetooth o, potencialmente, 802.15.4. El firmware que ejecuta el nodo se encuentra completamente desarrollado y validado al comienzo del presente proyecto, salvo la funcionalidad de envío a través de 802.15.4, que si bien está implementada en el dispositivo, no se ha probado de forma exhaustiva.

- *La familia de microprocesadores de 16 bits* MSP430 *de la firma* Texas Instruments

  Su elección se realiza teniendo en cuenta tanto su reducido consumo de energía como la sencillez en su programación, que permite utilizar C y depurar a través del estándar JTAG; pero principalmente por el hecho de que el nodo delineador ECG a emplear en el sistema utiliza esta misma familia de microprocesadores, y existe la posibilidad de reutilizar parte del código, especialmente el sistema operativo y la funcionalidad relacionada con envío inalámbrico a través de 802.15.4.

- *Sistema operativo de tiempo real* FreeRTOS *para dispositivos empotrados*

  El empleo de este sistema operativo viene determinado por la elección del nodo delineador, ya que éste emplea *FreeRTOS* y la implementación de la capa MAC 802.15.4 para dicho sistema operativo se encuentra disponible y puede ser aplicada en el proyecto. Es más, dado que el microprocesador que llevará el receptor a desarrollar es muy similar al del nodo delineador, el sistema operativo puede ser utilizado directamente en el receptor sin esperar la necesidad de muchas modificaciones. Como se menciona antes, la implementación de la capa MAC 802.15.4 para *FreeRTOS* implementación no está totalmente completa, pero es un buen punto de partida.

Cada tecnología se aplica en uno de los subsistemas que forman el sistema completo. Aunque se ha trabajado también con otras tecnologías, éstas se irán mencionando a lo largo de la exposición del desarrollo del proyecto que se realiza a continuación, y por tanto se omite su enumeración en este punto. Se analiza primero el desarrollo relacionado con la parte de hardware del proyecto.

El subproyecto de hardware contempla dos fases: por un lado la investigación sobre la factibilidad y la forma de alcanzar los objetivos propuestos, y por otro el desarrollo necesario para alcanzar dichos objetivos. Los objetivos concretos de este subproyecto son:

1. Lograr la comunicación de un microprocesador MSP430 mediante USB con el dispositivo Android

2. Inclusión de capacidad de comunicación a través USB en FreeRTOS

3. Empleo de 802.15.4 en FreeRTOS en el procesador MSP430 seleccionado

4. Asegurar la correcta operación de los módulos USB y 802.15.4 sobre FreeRTOS

5. Diseñar el circuito impreso específico para dispositivo receptor USB 802.15.4

6. Validación y producción del dispositivo receptor a partir del diseño

Debido a las restricciones de tiempo y de disponibilidad del equipo al tener que hacer frente a este subproyecto en paralelo con el desarrollo software, se toma la decisión de establecer estos objetivos como los hitos para la planificación, añadiendo uno extra que contempla una fase de prototipado inicial sobre una placa Arduino, que es bastante más sencillo que trabajar directamente con un MSP430 y sirve como toma de contacto inicial. Como se menciona anteriormente, los plazos para estos hitos se establecen tentativamente debido a la incertidumbre de cada objetivo.

Cabe mencionar que en lugar de separar las fases de investigación y desarrollo asociadas a cada objetivo se opta por no establecer límites fijos entre ellas, de forma que cada objetivo comienza con el planteamiento de las potenciales líneas de investigación del mismo. Seguidamente comienza el desarrollo de una de las líneas de investigación propuestas, y si se llega a un resultado negativo, se descarta el trabajo y se selecciona otra línea de investigación. Este sistema, cercano a las metodologías de desarrollo extremas basadas en prototipos, junto con la flexibilidad de la planificación propuesta ha resultado ser clave para la correcta consecución de los objetivos del subproyecto de hardware.

Detallamos ahora el proceso de desarrollo del subproyecto de software. Siendo este más cercano a un desarrollo tradicional, con menos incertidumbre en cuanto al resultado, se opta por aplicar una metodología de desarrollo ordenada con la que se asegure el cumplimiento de los plazos establecidos por el subproyecto de hardware. Debido a que se aplican las mismas restricciones temporales y de compartición de recursos que las expuestas anteriormente para el subproyecto de hardware, precisamente por la conducción de ambos en paralelo, se descarta la aplicación de metodologías de desarrollo con gran dependencia de la producción de artefactos, así como de metodologías que requieran planificaciones fijas.

Se opta, entonces, por la aplicación de una metodología híbrida entre una metodología iterativa y una metodología de desarrollo rápido. Esto se traduce en el establecimiento de una planificación inicial en base a los objetivos del subproyecto de hardware. Esta planificación empareja los hitos del desarrollo hardware con la funcionalidad correspondiente de la aplicación Android y, centrándose en construir la mayor cantidad de funcionalidad posible cuanto antes, distribuye el resto de objetivos del subproyecto software. Además es necesario asumir en todo momento la posibilidad de una modificación en las fechas.

Para hacer frente a ese tipo de contingencias se decide aplicar técnicas propias de metodologías iterativas como el análisis de riesgos y el desarrollo basado en casos de uso. De esta forma se mantiene el foco en el desarrollo de la funcionalidad clave aún cuando sea necesario un reajuste de los plazos o una mayor dedicación de recursos al subproyecto de hardware.

Los casos de uso identificados para el sistema son los siguientes:

- UC1. Visualizar datos obtenidos por Bluetooth
- UC2. Visualizar datos obtenidos por receptor USB
- UC3. Visualizar datos de un archivo de log
- UC4. Ajustar parámetros de visualización

Como el receptor USB 802.15.4 es la culminación de la investigación hardware, la planificación de los esfuerzos de desarrollo se plantea de forma que todo el resto de la funcionalidad se construya y valide mientras el subproyecto de hardware desarrolla un prototipo del receptor, y una vez se tenga este prototipo se proceda a la implementación de la funcionalidad relacionada mientras se desarrolla la versión final. Gracias a este tipo de planificación y al minucioso análisis de riesgos llevado a cabo durante todo el desarrollo, los objetivos del subproyecto de software también han sido alcanzados de forma satisfactoria.

Se ha logrado, entonces, la producción de un sistema de monitorización electrocardiográfica en tiempo real de bajo consumo y tamaño reducido empleando un dispositivo Android como interfaz con el usuario y el estándar 802.15.4 como protocolo de transmisión de datos inalámbrico. Este sistema provee toda la funcionalidad requerida: visualización de la onda ECG en tiempo real proveniente de nodos tanto 802.15.4 como Bluetooth, almacenamiento de ésta de forma permanente en archivos y su posterior visualización, así como capacidad para configurar los parámetros de la visualización tanto en tiempo real como de archivos. El sistema es, pues, una versión más accesible gracias al empleo de dispositivos Android y con un consumo energético dos órdenes de magnitud menor del sistema producido en 2011 por la Universidad Complutense de Madrid y la École Polytechnique Fédérale de Lausanne, lo cual es el principal objetivo del proyecto.

Este hito se alcanza gracias a la correcta finalización tanto del subproyecto de investigación hardware como del de desarrollo software en que se dividide el proyecto. Las diferencias en el enfoque requeridas por cada subproyecto sumadas a la estricta dependencia entre ambos resultaban una complicación añadida en la previsión del resultado de los dos desarrollos; pero, gracias a la aplicación de planificaciones flexibles pero de objetivos firmes en cada uno que no dejaban de tener en cuenta posibles complicaciones en el otro, y que contaban con planes tanto de contingencia como de actuación ante ellas, se manejaron correctamente ambos proyectos, dando lugar al actual estado de finalización satisfactoria del proyecto.

En cuanto al subproyecto de hardware, la producción del receptor USB de 802.15.4 para dispositivos Android se ha llevado a cabo con éxito. El dispositivo ha evolucionado desde las primeras etapas donde se empleaba una placa de prototipado hasta llegar a ser un circuito integrado diseñado expresamente para el proyecto. Este circuito integrado está completamente diseñado y validado, que en el momento en el que se escribe este documento está en proceso de fabricación. En su lugar se ha utilizado un prototipo, de tamaño algo más reducido pero construido a partir del diseño final de la placa, para la validación del sistema.

Las dimensiones del prototipo son 7.25 x 6.35 x 3.5 cm y necesita 3.3V de alimentación, aunque es utilizable a partir de 3.0V. La conexión USB es la que proporciona esta alimentación y además permite emplear el dispositivo en cualquier sistema capaz de comunicarse mediante HID, y ha sido probado con éxito tanto en dispositivos Android como en ordenadores ejecutando varias versiones de Windows.

Con respecto a la aplicación para terminales Android producida en el subproyecto de software, proporciona toda la funcionalidad que entra dentro de los objetivos del proyecto de forma robusta y con un diseño similar al de las aplicaciones canónicas de Android. Es una aplicación, dentro del dominio específico de la monitorización electrocardigráfica, con funcionalidad de propósito general, que requeriría cierta especialización para ser realmente útil. Esta especialización deberá añadir funcionalidad para el escenario de aplicación particular, y el análisis de esos escenarios o la posible implementación de alguno de ellos queda fuera de los objetivos del proyecto.

En cualquier caso, siendo conscientes de la necesidad de especialización futura de la aplicación, durante el diseño y desarrollo de la misma se puso un gran énfasis en que, además de ofrecer la funcionalidad requerida, proporcionase un conjunto de herramientas tal que pudiera actuar como un framework sobre el cual se pueda realizar el desarrollo de aplicaciones de monitorización ECG más específicas. Como detalle, mencionar que además de que el sistema está preparado para la inclusión sencilla de nuevas fuentes de datos además de Bluetooth, 802.15.4 y archivos, la fuente de datos de 802.15.4 en realidad es un dispositivo USB, en concreto el receptor, por lo que podría emplearse cualquier otro periférico que enviase datos con la codificación esperada en su lugar.

Esto da una idea de la flexibilidad buscada, y alcanzada, del sistema de monitorización desarrollado. Apoyándose en ella, se plantean potenciales líneas de trabajo futuro, distinguiendo entre las que se podrían realizar a corto plazo y las que serían ya para un medio o largo plazo.

Por un lado, un particular afectado de una enfermedad cardiovascular que requiere de monitorización electrocardiográfica constante, observando los objetivos y los resultados del proyecto actual, presentó al departamento un proyecto de especialización del sistema desarrollado para sus necesidades particulares, que son comunes al colectivo de afectados por dicha enfermedad. Este nuevo sistema ha de incorporar, además de la funcionalidad presente en el actual, algunas características nuevas:

- Etiquetado de eventos durante la delineación, de forma que el usuario pueda indicar al sistema en qué momentos se encuentra mal y la información quede almacenada junto a la onda ECG. De esta forma podría estudiarse posteriormente la información guardada de forma más detallada para mejorar la compresión del estado del paciente.

- Adición de información temporal a los logs, de manera que el usuario pueda consultar directamente la onda ECG relativa a un momento concreto en el que se encontró mal, o que pueda saltar al momento indicado por un marcador de eventos. Esto facilitaría la consulta y navegación por los datos almacenados.

- Comandos de voz que permitan interactuar con el sistema sin necesidad de emplear las manos, ya que, ya sea por su estado de salud o porque las tenga ocupadas, es posible que el usuario no pueda manejar la aplicación.

- Avisos automáticos en caso de que se produzca algún evento relevante relacionado con la salud del usuario, de manera que se pueda alertar al mismo, algún pariente o personal cualificado en caso de ser necesario. Además, estos avisos podrían hacerse de varias formas, ya sea a través de mensaje, correos electrónicos con localización GPS adjunta o incluso llamadas de voz automáticas directamente.

Por otra parte, se contemplan una serie de expansiones del sistema más a largo plazo, debido sobre todo a que requieren de más tiempo y recursos, aparte de una planificación específica. En primer lugar se proponen mejoras enfocadas a la monitorización de varios pacientes, para un entorno más profesional, en dos posibles versiones:

- Dado que el receptor desarrollado también es compatible con dispositivos que soporten el protocolo HID, se propone utilizarlo conectado a un PC que actúe como servidor, recibiendo los datos ECG procedentes de los nodos de varios pacientes. Una vez estos datos están en el servidor, la propia aplicación Android permitiría conectarse a este para descargarlos y visualizarlos en el dispositivo.

- Teniendo en cuenta que la pantalla de un tablet es relativamente grande, se puede aprovechar para mostrar los resultados de la monitorización de varios pacientes a la vez. Como parte de esta nueva funcionalidad también se encontraría la de cambiar entre la onda ECG de otros pacientes, guardado de logs simultáneo y subida a un servidor dedicado.

También a largo plazo, aunque en el campo de la automonitorización, se plantea la adaptación del sistema a dominios particulares que imponen requisitos adicionales debido, sobre todo, al entorno en el que se utilizaría. En este sentido, el director del Laboratorio de Sistemas Empotrados (ESL) de la EPFL (equipo responsable junto a la UCM del desarrollo del nodo delineador que se usa en este proyecto) ha mostrado interés en la aplicación de los bajos requisitos de consumo del sistema en otro proyecto de la EPFL con el que está colaborando, el Solar Impulse.

Este proyecto en concreto trata de conseguir un vuelo alrededor del mundo evitando el uso de carburantes de cualquier tipo, utilizando únicamente energía solar. El avión utilizado es de una única plaza, por lo que las constantes vitales del piloto deben estar monitorizadas en todo momento. Por el momento, la monitorización electrocardiográfica se lleva a cabo utilizando el sistema desarrollado por la UCM y la EPFL, con la escasa duración de batería que ello implica.

Teniendo en cuenta que el espacio dentro de la cabina es muy reducido, cualquier tarea debe ser llevada a cabo con especial cuidado y únicamente cuando sea absolutamente necesario. Es por ello que el intercambio de la batería del nodo delineador debe ser una tarea lo menos frecuente posible, entre otras razones porque interrumpe la monitorización en el proceso.

Por tanto, la reducción del consumo de energía y el consiguiente aumento de la duración de la batería plantean un avance muy significativo para un proyecto como el del Solar Impulse, tarea que se puede conseguir mediante el empleo del estándar 802.15.4 como protocolo de comunicación inalámbrico.

Llegados a este punto, con el proyecto finalizado y habiendo analizado el estado final del mismo, así como algunas de las potenciales líneas de trabajo futuro, parece relevante plantear algunas conclusiones alcanzadas durante el desarrollo a modo de conclusión.

En la fase de inicio del proyecto, incluso habiendo ya decidido el emplo de un dispositivo Android como la interfaz para mostar los datos en tiempo real, el equipo tenía cierto recelo acerca de la aplicación de Android como base para el desarrollo de aplicaciones con las restricciones de tiempo real como las que imponía el proyecto. Durante el proceso de desarrollo el hecho de que Android posiblemente no sea la plataforma más adecuada para este tipo de funcionalidad se hizo patente ya que, incluso con la potencia de cómputo y las capacidades gráficas de los dispositivos actuales, las restricciones impuestas por el sistema operativo complican considerablemente la implementación fiable de funcionalidad en tiempo real.

En un sistema como el desarrollado en este proyecto el empleo de un dispositivo especialmente dedicado a la visualización y almacenamiento de datos en tiempo real hubiera permitido un nivel mayor de fiabilidad, e incluso una representación más visualmente atractiva, cumpliendo además con las restricciones temporales, pero los beneficios de utilizar Android compensan ampliamente este tipo de carencias.

Entre los más importantes de estos beneficios, al menos en el ámbito del proyecto, se encuentran la sencillez en el desarrollo de aplicaciones para Android, que simplifica la ampliación del sistema en el futuro, y, aún más relevante, la amplia difusión de estos dispositivos entre el público general, de forma que el sistema es mucho más accesible. Si bien estos beneficios se han tratado a lo largo de todo este documento, se antojaban merecedores de una última mención. La selección, pues, de Android como plataforma para la aplicación del sistema puede considerarse como una de las decisiones más acertadas del proyecto.

Incluso con la sencillez que Android aporta a la parte de desarrollo software, procesos de desarrollo como el llevado a cabo en este proyecto, que dan lugar a subproyectos de diferentes características y con dependencias entre ellos, pueden llegar a ser empresas inalcanzables si no se encaran de manera adecuada. Más aún, en este caso concreto el carácter principalmente de investigación de la rama de desarrollo hardware no hacía sino complicar el planteamiento del proceso.

Durante el desarrollo del proyecto se han aplicado algunas técnicas que han probado ser de gran relevancia para la correcta finalización del mismo. Las más relevantes son, como se expone anteriormente, el empleo de una planificación flexible que admita modificaciones, ya que debe basarse en suposiciones la mayor parte del tiempo; la utilización de un proceso de gestión de riesgos minucioso para contrarrestar las dificultades producidas por los potenciales cambios en la planificación y el mantenimiento del foco sobre el objetivo actual, sus plazos y dependencias, gracias a una metodología de desarrollo basada en casos de uso. Gran parte del éxito en la satisfacción de objetivos de este proyecto puede otorgarse a la aplicación rigurosa de las técnicas anteriores.

La importancia de los sistemas de monitorización para colectivos afectados por enfermedades cardiovasculares específicas ha quedado patente durante el desarrollo del proyecto. Este área presenta un gran potencial de desarrollo, especialmente si se considera que estos sistemas van a ser utilizados en su día a día por la gente que los necesite. Los proyectos surgidos en este área deben considerar siempre al usuario final durante todo el proceso de desarrollo ya que un pequeño esfuerzo de cara a este, como reducir el número de operaciones requeridas para iniciar la visualización o simplificar la manera en que se interactúa con la aplicación, por pequeños que puedan parecer los efectos, puede mejorar sensiblemente la calidad de vida del usuario. Esto es así porque molestias aparentemente inocuas en la interfaz de usuario, por ejemplo, pueden convertirse en una fuente constante de frustración cuando la aplicación se utiliza día tras día.

Mediante la producción de un monitor ECG de bajo consumo energético se contribuye a este fin disminuyendo la cantidad de interrupciones que sufre el proceso de monitorización debido a la necesidad de efectuar la carga de la batería del nodo delineador con la consiguiente alteración del ritmo de vida normal del usuario. Gracias a la aplicación del protocolo de comunicación inalámbrico 802.15.4 la vida de la batería se incrementa en dos órdenes de magnitud, lo cual se traduce en tener que cargarla una vez a la semana en lugar de dos veces al día.

En la misma línea, la utilización de Android en lugar de iOS permite que la aplicación de monitorización, que muestra y, más importante, almacena los datos de la onda ECG en tiempo real trabaje en segundo plano de forma que su ejecución no se ve interrumpida por eventos comunes como una llamada telefónica entrante o la necesidad de buscar algo en Internet empleando el dispositivo. Otra característica importante que proporciona Android es la capacidad de las aplicaciones de continuar su ejecución cuando el dispositivo entra en modo de ahorro de energía, por ejemplo apagando la pantalla. Como antes, esto puede parecer algo anecdótico, pero para una persona que necesita monitorización constante se trata de características de gran importancia ya que afectan a la actividad que realiza en su vida diaria.

Como confirmación de estas afirmaciones, durante las fases finales del desarrollo del proyecto, antes incluso de haber comenzado el proceso de validación, el particular afectado de una enfermedad cardiovascular antes mencionado contactó con el departamento en el que se desarrolla el proyecto y mostró gran interés en el mismo tras ser informado de los objetivos y resultados alcanzados. La interacción con esta persona produjo el proyecto futuro explicado anteriormente para la especialización del sistema desarollado a las necesidades de la enfermedad particular. Además, esta persona se encuentra actualmente realizando una prueba del sistema en un escenario de aplicación real como es su caso, los resultados aún por llegar en el momento de escribir el presente documento, y está dispuesto a colaborar en todo lo posible con el proyecto y sus futuras evoluciones, ya que le pueden ser de gran ayuda.

Es más, como se menciona antes, el director del Laboratorio de Sistemas Empotrados (ESL) de la EPFL está interesado en los resultados del proyecto para aplicarlos al proyecto *Solar Impulse* con el objetivo de monitorizar continuamente al piloto del aeroplano solar. La nave está equipada con un dispositivo tipo tablet para varios fines, y la utilización del mismo como visualizador de la monitorización, así como la reducción del consumo de batería del nodo delineador tanto como sea posible debido a lo crítico del ahorro energético en el vuelo solar, constituyen un gran escenario para la aplicación de los resultados del proyecto.

Es comprensible, entonces, que estas muestras de interés en el proyecto convierten el desarrollo en un éxito independientemente del resultado final. El hecho de que el trabajo realizado durante los últimos meses se confirme como capaz de proporcionar beneficios reales a determinadas personas, lo cual era, en el fondo, el objetivo último del proyecto, hace que todas las dificultades del proceso sean meramente anecdóticas al compararlas con el orgullo personal que, en efecto, proporciona.

Chapter 1

Introduction

1.1 Project description

This document exposes the research conducted for the development of an USB 802.15.4 receiver device for Android based systems employed in a fully functional electrocardiogram monitoring system encompassed in the field of in-home healthcare, as well as the development process involved in the realization of this whole system.

Electrocardiogram (ECG) monitoring consists of the capture and interpretation of the activity of the heart during a period of time, and continuous, remote ECG monitoring has become one of the main applications of wireless body sensor networks. Great interest has arisen recently among industrial and academic research parties in production of low-power, ambulatory ECG monitoring systems.

In order to maximize portability, such systems have started to employ the widely available smartphone devices as frontends, reducing the amount of extra devices carried by the user to just the ECG capturing node. In 2011 the Complutense University of Madrid (UCM) in collaboration with the École Polytechnique Fédérale de Lausanne (EPFL) presented a real-time personal ECG monitoring system which displayed data in an iPhone via Bluetooth [1].

Being inspired by the results obtained by the aforementioned project, this certain endeavour seeks taking the inherently good low cost and low power aspects of that to the next level by the employment of a less energy requiring wireless personal area network protocol, namely IEEE 802.15.4, and the more accessible Android based platforms.

The system which is to be developed in this project provides the user with a visual representation of his/her ECG wave in real-time highlighting relevant points of this in order to simplify its comprehension. Information about heart-beat-rate is also displayed. All this data is stored in a transparent to the user manner for later visualization with emphasis put in easy handling of the generated files.

This functionality is provided by the three devices that are part of the system: the ECG delineation node, the USB 802.15.4 receiver and the Android device through the front-end application. The ECG delineation node is connected to the body sensor network and is responsible for capturing and analyzing the electrocardiogram wave, as well as encoding and wirelessly sending the data. The USB 802.15.4 receiver is plugged to the Android system and manages data reception following the aforementioned protocol. Finally the Android based application is the real-time data decoder and acts as the frontend to the user, managing connections and storing and displaying received data.

Development of the Android application, realization of the real-time USB 802.15.4 receiver device, employment of an already-existant ECG delineation node and successful intercommunication between all these elements are the project goals.

As stated before, the Android application is the front-end with which the user interacts with the whole system. It is designed following Android common practices as the objective is for it to be of simple use with a smooth, if not nil, learning curve. The decision to develop the application for Android platforms was made according to three main reasons:

First, the fact that Android has been in the top three of the most used mobile operating systems rankings since 2010 [2] added to the recent growth of the availability of smartphone devices [3] makes targeting the Android platform a must when the objective is making the system reachable for as most people as possible.

Second, and following the same line of reasoning, the lower cost, in general terms, of Android supporting devices, or at least the wide range of prices of these, specially when compared to other operating systems supporting devices such as Apple's range of iOS devices is to be taken into account.

And finally the comfortable, high-level development environment available for Android application production [4] provides enough facilities for anyone interested in expanding or contributing code to the Android part of the project to do so in an easy way. Moreover, this environment is delivered free of charge and is of an open-source nature and multiplatform [5], whereas iOS platform development kits usage requires at least the ownership of an specific machine and operating system [6].

Regarding the ECG delineation node, it has been mentioned that the objective of this project is the employment of an already existing one. That is so because both the delineator node and the body sensor network that captures the data are complex systems and the development of them would be the scope of a full project. Specifically the delineator node obtained in the aforementioned project [1], with modifications from another collaboration between the UCM and the EPFL [7], was applied.

This node was originally developed as a ultra-lowpower real-time ECG delineator with the ability to wirelessly send data through Bluetooth protocol. The collaboration between UCM and EPFL, among other things, provided the node with functionality to send data using IEEE 802.15.4, but only at the level required to do some measurement and estimations [7]. Actual 802.15.4 utilization was yet to be a reality, but it was an excellent starting point towards the achievement of the current project objectives.

The key part of the system and the most important risk involving objective of the project is the real-time 802.15.4 USB receiver device for Android platforms. It is a necessity as Android devices generally have no support for low cost wireless communication protocols such as 802.15.4, while providing other higher-cost protocols such as Bluetooth or Wi-Fi. Development of an Android accesory providing the required functionality is, then, a must, as the most battery and time consuming operation in the delineator node is the utilization of the Bluetooth stack, as previously mentioned researches [1] and [7] concluded.

Other projects exist with the objective of achieving 802.15.4 reception for Android devices, even if they are not targeted at the field of biomedics and personal monitoring. The reason for not following or employing those is twofold: first, at the time of the beginning of the project those initiatives were either unfinished or stalled (as it can be seen in [8]), furthermore they were isolated, generally single-man projects with no official backend or guarantees of conclusion. Second, following the line of achieving a low energy, low sized device the Android system of this project is to act as the host device in the USB communication, thus removing the size-increasing battery requirements for the receiver as the host role provides the power in such communications. None of these projects employed the host capability of Android devices, so they were of no use for the pursued objectives.

In short, this project tries to advance a step further the availability of wireless body sensor networks applied to personal electrocardiogram monitorization, by employing actual, already available, not-so-expensive technologies in an effective manner. That is necessarily good by nature, and the main motivation for braving with the project, aside from those, more pragmatic, exposed in the next section, is the wish for it to be useful, some day, for someone.

1.2 Project driver

The motivation for the realization of this project comes from two different areas: the further potential utility of the project and the academic interest it involves.

The potential utility of the project point of view is developed first.

Cardiovascular diseases are the number one cause of death globally, according to the World Health Organization [9]. The level of supervision required by affected people is usually not assumible by traditional health care institutions, and constant, in home monitorization is an objective yet to fulfill which can be of great help for affected inviduals.

In such an scenario wireless body sensor networks (WBSN) prove to be inexpensive, efficient monitoring tools. Specifically electrocardiogram monitoring applied WBSN are of great utility for constant tracking of cardiovascular diseases, and projects as the aforementioned UCM and EPFL collaboration pursue the realization of a wide employment of these systems.

The employment of smartphone devices as the monitoring display of the system targets the wide spreading of the application of these systems, and reduces the amount of devices to be carried by the user. The selection of Android as the base platform for the display part this project, as explained before, is made attending to two factors: the higher expansion of the Android operating system when compared to others, and the flexible, open-source nature of it. These are key for the further expansion and application of the system.

Reducing battery and size requirements also targets a higher employment of the system by simplifying the usage procedure: lower battery requirements involve less monitoring interruptions due to the charging of the system and lower sized devices allow higher portabilty and more constant monitorization. The employment of the 802.15.4 wireless protocol seeks the fulfillment of this objectives.

In conclusion, the employment of an 802.15.4 receiving enabled Android device in a real-time, continous ECG monitoring system reduces the battery and size requirements for the system, maximizing portability and lessening the restrictions on the applicability of it.

From an academic point of view, the main motivation for the development of this project is the fact that it means the gathering of almost every branch of the Computer Science and Engineering career. From its very beginning, the project involves both software and hardware development, researching on out of the scope of the career tools and platforms as well as high and low-level design and programming.

It is also expected that technologies based on IEEE 802.15.4 specification like ZigBee will increase their importance in the medium term due to their potential applications in domotics (home automation) and other areas.

In addition, both the development of applications and accessories for smartphones or other portable devices are mainstream, highly demanded activities nowadays and getting in touch with these provides extra experience at leading edge practices, which broadens our areas of expertise and, consequently, increment our value in the labour market.

1.3 State of the art

- *UCM and EPFL ECG monitoring Project*
  As a precedent of the present project, the Complutense University of Madrid (UCM), along with the École Polytechnique Fédérale de Lausanne (EPFL) –represented by its Embedded Systems Laboratory (ESL)–, developed a wireless ECG monitoring system [1], similar to the one has been built up during this project.

  Just as ours, this system also used Shimmer™as monitoring, transmitter platform (details about it can be found at subsection 2.3.3); and the obtained data could be displayed in portable computing devices. Nonetheless, the list of similarities ends there. The application responsible for rendering the ECG waves was meant to be used over iOS devices, particularly iPhone. This fact led to several additional restrictions, such as mandatory usage of Bluetooth as wireless transmission method as well as the need of "jailbreaking" the device itself. This process allows the user to gain root access to the OS, and it was needed in order that a explicitly installed Bluetooth stack allowed the device to receive the emitted data properly. However, according to the manufacturer [10], jailbreaking the device nulls its warranty. Therefore, the employment of Android in our project is partially motivated by this sort of limitations other platforms usually impose.

  Whereas the UCM was responsible of the delineation algorithm, the development of the iOS application was carried out by the EPFL, and thus the development of this project depended on the feedback and requirements (hardware and software) both of them provided. In fact, the aforementioned iOS application settled most of the requirements for the Android one in this project, although there were added some extra ones –such as making logs from received data so they can be read again later–.

- *IEEE 802.15.4*
  This standard describes the physical and Media Access Control (MAC) layers for low-rate wireless personal area networks. It is intended to be implemented into embedded devices, so as to build up short-range networks –10 meters, typically– with narrow bandwith, up to 250kbps,

among other possibilites with lower transfer rates. It is a relatively new standard since its first version was approved in 2003, although the following revision was employed during this development, which was approved in 2006 [11].

802.15.4 is specially suitable for this kind of project due to its low power consumption. In fact, ZigBee, which uses this standard as its low-level layer, presents a series of advantages over Bluetooth, underlying technology of the previously mentioned EPFL and UCM project:

- **Lower power consumption:** without going into detail, it can be stated that Bluetooth requires more power than ZigBee does. For example, Bluetooth is constantly emitting information, consequently consuming power, while 802.15.4 allows to enable the radio only when it is needed. These statements are properly justified and explained at subsection 2.3.4, *802.15.4*.
- **Bandwidth:** Bluetooth offers much wider bandwidth, up to 3Mbps, meanwhile ZigBee only offers up to 250kbps. This, however, is not a relevant disadvantage because the requirements of the system are not so demanding.
- **Host number:** ZigBee allows to build networks with up to 65535 hosts, subnetworks with 255 hosts. On the other hand, Bluetooth can only support as much as 8 hosts within a network.

ZigBee, though, is not employed as a whole within this project, but 802.15.4 standard as its basis (its MAC layer, more precisely). Nevertheless, its advantages over Bluetooth remains the same, with the additional one that it does not compromise real-time developments as the complete stack does.

- *Android Accessory Development*
  As of May, 2011, there were no easy nor official methods to develop accessories capable of communicating with Android running devices. At that certain time, the release of the Android Open Accessory Development Kit (also known as “ADK”) [12] was announced in San Francisco, within the context of Google I/O, developers conference arranged by Google [13].

ADK consists of an USB microcontroller board based on Arduino (Arduino Mega2560 to be precise) and a series of software libraries which add specific functionalities and support for other hardware add-ons, typically known as *shields*, that equip the accessory with sensors or interactive elements which broaden its capabilities. Shields are plugged to the board through its numerous input/output pins, which also allow the connection of personally crafted hardware additions –allowing that way to create tailored behaviours, following the Arduino's "Do It Yourself" (DIY) spirit.

With the release of that kit, Android project opened itself to the development of all kind of new accessories which would add potential and functionalities it lacked.

As well as this kit, the following release of Android 3.1 API version completed the accessory ecosystem with the inclusion of directly supported host and device USB modes –this support was also backported to Android v2.3.4; only the device mode, though–. By doing so, Google completely cleared the way for the development of Android-compatible accessories, which was previously reduced to the underlying, quite complete but not enough, Linux kernel driver support.

- *ZigBee dongles*
  In spite of the fact that there were available devices which implemented the complete ZigBee stack at the time of the start of this project, they were only designed for being connected to personal computers, some models with OS restrictions as well. A typical model of this sort is presented in [14].
  Moreover, even if they were to be compatible with our target device, the only available dongles fully implemented the ZigBee stack, which also made them unsuitable for this project due to the relatively high latency that fact imposed –as it can be read at subsection 2.3.4, *802.15.4*, real-time needs required the usage of the 802.15.4 MAC layer on its own–.

- *Communication with Android using ZigBee*
  One year ago, around mid-2011, there were very few projects which were working on this sort of communication, between Android and

802.15.4 radio-equipped devices. Concretely, the only noticeable project of this kind was one from Texas Instruments, which was stated to be pioneer in this field (as it can be seen in [15]). Despite that, several differences stands between this project and the present one. For instance:

- **USB communication:** Texas Instruments developed its own Android driver, namely "virtual COM port", so they could directly connect their ZigBee Network Processor (ZNP) to the Android device through USB. Instead, Android USB host mode is used in this project in order to establish the connection between the receiver and the device. Because of using this method, USB communication between MSP430 microcontroller and the Android device has to be specifically implemented and tuned.
- **Android platform:** TI's project employed Android 2.2, while version 3.1 is the one employed in this present project, due to the aforementioned need of USB host mode support this API provides. In addition, received data is used by this Android application, while TI employed ZigBee communication for less specific ends, such as controlling other devices like PCs, lamps or obtaining data from certain sensors.
- **Wireless communication:** in order that the ECG delineation could be done in real-time, this project does not use the complete ZigBee stack, but its 802.15.4 MAC layer. This restriction requires the radio –in particular, TI CC2420 radio module– has to be programmed specifically. Meanwhile, Texas Instruments made use of its TI CC2530 system on chip (SoC), which fully implemented ZigBee stack.
- **USB dongle:** as it was mentioned before, TI directly plugged their ZNP to an OMAP4 Blaze thanks to their driver. However, so that the same result could be obtained, the radio, CC2420 module, had to be connected to the MSP430 board, namely the MSP-TS430PZ100USB, which was equipped with a USB interface. Furthermore, miniaturisation of this board was designed afterwards to make it an usable dongle.

In other words, Texas Instruments' project was actually able to build up working communications of this kind by the time ours was starting; all the same, special requirements like real-time needs entail additional challenges for this project to overcome.

1.4 Document overview

This document presents the process involved in the realization of the project objectives. Discrimination of the hardware and the software parts of this process is mandatory, as the approach for each one, the applied methodologies and techniques as well as the development processes, differ.

The first chapter, this introduction, gives a global view of the project. A description of the project providing a detailed depiction of the objectives pursued, as well as the inspiration for it's development and an exposition of technologies applied is elaborated in section 1.1 *Project description.* The motivation leading to the undertaking of such project is presented then, explaining the reasons both from the project potential utilization and the academic interest of the project points of view. This explanation is conducted in section 1.2 *Project driver.* The next section, section 1.3 presents the state of the art regarding the technological fields and technologies involved in the project. The chapter concludes with this overview of the document in section 1.4 *Document overview.*

The research and development of the hardware part of the project in order to obtain the 802.15.4 USB receiver is presented in chapter 2, *Hardware and Communications.* It begins exposing the specific objectives pursued by this part of the project and providing an overview of the chapter in section 2.1, *Introduction* and section 2.2, *Overview.* A detailed description of the technologies employed in the hardware development process is then provided in section 2.3, *Technology Research.* The specific process, methods and techniques applied in the hardware development are presented in section 2.4, *Description.* The remaining part of the chapter is devoted to the description of the actual research and development conducted throughout the whole project time. First, an explanation of the project schedule, as well as the specific circumstances which led to it being as it is, is provided in section 2.5, *Milestones*, followed by detailed exposition of the development of each stage of this schedule. The chapter concludes with the analyisis of the final hardware product and an exposition of the conclusions obtained during the process in section 2.6, *Closure.*

The third chapter, *Software Development*, explains the process followed for the production of the Android application which acts as the ECG monitoring front-end employing artifacts from structured software development methodologies so as to provide an in-depth view of the software part of the project. In section 3.1, *Introduction* and section 3.2, *Overview* a brief description of the software project and an explanation of the information contained in the scope of the chapter are presented. The identified requirements for the project, both functional and non-functional, are presented in section 3.3, *Requirements*. In the next section, *Risk Analysis*, the importance of the risk management for this particular project is demonstrated and the identified risks exposed, including their evolution throughout the project development. The analysis process view concludes with the exposition of the use cases for the system in section 3.5, *Use Cases*. The *Design and Architecture* section presents the architectural view of the system, explaining design considerations and system modules in a comprehensive manner. The project development process is exposed in section 3.7, beginning with an explanation of the software project schedule which is followed by detailed descriptions of each of the project scheduled iterations, including risk evolution and use case realization related information. The chapter concludes with a review of the software project development in section 3.8, *Closure*.

In the final chapter of this document a review of the project as a whole is conducted. First, the final state of the system is presented in section 4.1, *Final state*, detailing the accomplishment of each project objective so as to evaluate the project outcome. Taking the final state of the project as the starting point, potential further work lines are proposed in section 4.2, *Potential additions and expansions*. Finally, as a closure to both the document and the project, section 4.3, *Findings* explains the conclusions drawn from the development of the project.

Three appendices are attached to this document. The first of these, Appendix A, *Budget Analysis* presents an estimation of the cost of the project including performed tasks and scheduling in section A.1, as well as a Gantt chart for this scheduling in subsection A.1.2, *Software project tasks*. The total cost of the development is exposed in section A.2, *Asset cost*.

Appendix B, *Product Cost* refers the cost of the production of both a single unit and a batch of ten thousand units of the receiver device, the latter as an estimation of the costs in a mass production scenario.

The documents produced in the process of design and development of the receiver device are presented in Appendix C, *Receiver Specification Documents* with enough detail to allow custom production of the device. The bill of materials, the device schematic and the printed circuit board design are also included.

Chapter 2

Hardware and Communications

2.1 Introduction

The hardware research and development part of the project objective is covering a main need: production of an external device that enables communication between an Android system and a Shimmer through 802.15.4. Such a device should be a portable and low-powered device that can be plugged via the widely used USB On-The-Go (USB OTG) to a host Android system, acting the device as a slave.

It has to be small sized because of the target application environment: a particular who requires constant, in-home, ambulatory monitorization. In that scenario unobtrusive operation is a main need, and usual life style activity modification is to be minimized. And it has to be low-powered, because were the power cost of application higher than that of the Bluetooth technology, a main advantage of 802.15.4 is lost.

The ability to communicate through USB is required because, at the time, it is the most low battery consuming method to interact with Android powered platforms for any external device.

And finally it should be able to act as the slave in the USB connection to avoid the need of an extra power source for the device that would increase the cost and size of the product.

In order to achieve such goals, and being aware of the substancial amount of research involved in this part of the project, the decision is made to adopt a milestone driven development which simplified scheduling and helped focusing on specific tasks while maintaining a global view of the evolution and the objectives of the project.

2.2 Overview

Before diving any further into the development a section describing technologies involved in the research process is presented, as such information will be key to the understanding of the rest of the chapter and will be throughoutly referenced during the exposition.

Then a description of the hardware research and development process is given, followed by detailed explanation of each projected milestone, including objectives pursued, lines of research developed, results of each one and conclusions obtained. Estimation based decision making being crucial for the correct outcome of the project, special care will be put to explain the motivations for each decision made. The chapter concludes with an exposition of the results of the research and subsequent development.

2.3 Technology Research

This part of the project involves a lot of terms and references a number of technologies and concepts which are important to be acquainted with in order to achieve a full understanding of the current chapter. These explanations will not be presented interlaced with the rest of the sections due to the unmanageable size they would acquire leading to a loss of focus which can only act against full comprehension of the exposed content.

2.3.1 Google ADK & Arduino

Android Open Accessory Development Kit, referred as "Google ADK" or "ADK" for now on, is a tool set which allows the development of accessories capable of interacting with Android-running devices. It consists of an Arduino board (particularly MegaADK, which is based on the ATmega2560 board) and a series of libraries for interacting with an optional set of hardware add-ons ("shields"). There are other compatible kits with different boards, like NXP-based mbed [16], yet Arduino MegaADK is the one used here.

The Google ADK functioning is actually very simple. Regarding the software, it requires the development of both an Android application with accessory communication capabilities and the proper firmware of the board, which models the behaviour of the accessory. Once the board is flashed with its firmware, it has to be connected to a power source (through a dedicated wire or Type-B USB) and the Android device. If everything is correct, the latter detects the former and, therefore, the accessory starts its operation.

Typically, the capabilities of the Arduino board are broaden with the addition of extra shields, so that way it can make use of external sensors and agents. The board has multiple input and output pins at the developer's disposal as well, so unforeseen behaviours can be achieved.

2.3.2 MSP430

MSP430 refers to an entire family of 16-bit CPU microcontrollers from Texas Instruments [17]. Its most relevant features are:

- **Very low power consumption:** its several low-power modes make the MSP430 family specially suitable for developing embedded systems. Moreover, its brief wakeup transitions from this operating modes are also noteworthy, since these lapses stay around the microsecond (μs) range.

- **RISC-based Architecture:** its instruction set is particularly narrow [18], and thus simple. Reduced instruction sets ease programming when compared to complex ones, yet this advantage is not too decisive because of the reason presented next.

- **Simple programming:** Most family members are programmable trough JTAG, which makes the debugging process less difficult along with the possibility of swapping assembly for C.

- **Wide support and resources:** Texas Instruments provides code examples, software IDEs and thorough documentation as well as it offers extra development tools like training boards.

However, it also suffers from some lacks. For instance, MSP430 devices are not equipped with an external memory bus, what makes flash memory and RAM extensions impossible. In particular, the MSP430F66xx family, which the device used within this project belongs to, is provided with only 128-256KB of flash storage and 16KB of RAM –with an extra of 2KB whenever it is not using USB [20, p. 2]–. This amount of RAM may be too limited for certain usages (not for this project's particular requirements, though).

Concretely, the microcontrollers and boards used in this project are:

- **Microcontrollers:** *MSP430F5438A* vs. *MSP430F6638*
  Both of them are characterized by their low power consumption as well as their voltage range, from 1.8V to 3.6V. Although they share most of their specs, there are some points where they differ:

  1. **System Clock Frequency:** in the case of the MSP430F5438A microcontroller it is up to 25MHz, whereas MSP430F6638's clock only reaches 20MHz.
  2. **Wakeup time lapse:** meanwhile TI claims MSP430F5438A wakes from standby mode in less than 5μs, MSP430F6638 needs less than 3μs.

  However, the most important difference lies in the USB support the second microcontroller provides, which is the reason why it was chosen for the accessory development. At any rate, full technical specification can be found at [19] and [20] for MSP430F5438A and MSP430F6638, respectively.

- **Boards:** *MSP-EXP430F5438* vs. *MSP-TS430PZ100USB*
  MSP-EXP430F5438 [21] is a prototyping board designed to make use of microcontrollers from the family of MSP430F5438 and stands out for featuring the following sensors and input/output elements: USB, JTAG, 5-position joystick, 2 push-buttons, dot-matrix LCD display, accelerometer... (full list of features in [21]). Furthermore, it also equips the *CC2420*, 2.4 GHz 802.15.4 radio module, which make this board specially convenient for this project's requirements. This module is directly connected to the microcontroller allowing their communication through SPI. In addition, its USB connectivity provides a very useful serial output for debugging.

Nonetheless, despite the wide possibilities the previous board offers, the MSP-TS430PZ100USB [22] is selected. This board lacks serial port output and CC2420 compatible sockets, so the connection is to be done by hand and nor any of the other aforementioned artifacts available in the MSP-EXP430F5438 is present. But it provides the key feature required by the project: the ability to communicate the microprocessor with the board's USB connector.

2.3.3 Shimmer™

Shimmer [23] is a trade name which refers to a wireless sensor platform designed to obtain, deal and wirelessly transmit human biological metrics and several ambient and kinematic measures. The whole system consists of the Shimmer platform itself and a series of extensible sensor modules as its hardware part, an open source firmware library and software development tools.

After its proper firmware programming, the platform is capable of retrieving the aforementioned data thanks to its expansion modules [24] so that the user can manage it as considers. Once the data is appropriately dealt, the Shimmer is able to wirelessly send it via Bluetooth or 802.15.4 to other receiver nodes, which may be Shimmers or another compatible device.

In order to carry out its tasks, the baseboard of the Shimmer is powered with a MSP430F1611 microprocessor as CPU, which belongs to the MSP430 microcontroller family previously detailed. Additionally, the Shimmer is also equipped with Bluetooth and 802.15.4 radio modules which perform the data sending as well as several input/output devices and sensors –three LEDs, one push button, accelerometer and a microSD socket, among others–.

Its usage is typically focused on healthcare or remote patient monitoring applications due to its small size and weight and its relatively low power consumption (which strongly depends on the employment its resources are given). In fact, the manufacturer itself refers to the Shimmer as "wearable wireless sensor platform". In addition, its multiple sensors allow many other applications like athlete performance monitoring or ambient sensing solutions.

This sort of platform is employed at the ECG monitoring project [1] developed by the EPFL and UCM which, conveniently adapted, performs as the emitter part of the present project. In particular, the system described within this document makes use of the 802.15.4 communication capabilities the Shimmer platform provides, which mean a key feature of this project.

2.3.4 802.15.4

The 802.15.4 standard [11] was first developed by the Institute of Electrical and Electronics Engineers (IEEE) in 2003, and was updated with successive revisions in 2006 and 2011. This standard sets the specification for the physical layer and Medium Access Control (MAC) of low-rate wireless personal area networks (LR-WPANs [11, p. 13]). This sort of networks, in the same way that affects WPANs, involves little or no infraestructure, fact that allows the implementation of inexpensive and power-efficient solutions for devices of different kinds, when compared to more end-user oriented wireless local area networks (WLANs).

As said, this sort of WPANs are intended to be used when having limited power and relaxed throughput requirements (concretely, narrow bandwitdth need, up to 250kbps), as they aim for simple, easy-to-install short-range networks with little power consumption and low budget. To meet these objectives and requirements, the 802.15.4 standard makes use of one or more of the following unlicensed bands:

- 868-868.6MHz in Europe.
- 902-928MHz in North America.
- 2400-2483.5MHz can be employed worldwide.

Two kind of devices are considered within the standard: full-function (FFD) and reduced-function devices (RFD). FFDs are capable of communicating with both other FFDs and RFDs, whereas RFDs can only communicate with FFDs (RFDs are supposed to have very simple responsibilities, minimal resources and, consequently, send little amounts of data). These devices are to be arranged in peer-to-peer or star topologies. Concretely, devices in this project are arranged using a star topology where Shimmer emmiter nodes are RFDs which communicate with the receiver node FFD, the MSP430-based device connected to the Android tablet.

Regarding the MAC layer, it allows the usage of superframes instead of discrete frames. A superframe is bounded between two beacons sent by the FFD coordinator, which also defines the format of the superframe. The lapse between two consecutive beacons is equally divided into 16 slots, and may or may not be divide into an active and an inactive period, in which the coordinator may enter a low-power mode. Particularly, in this project, part of the superframe is divide into portions called *guaranteed time slots* (GTSs), which form the *contention-free period* (CFP) at the end of the superframe, after the *contention access period* (CAP), as it is represented in Figure 2.1. One GTS can use more than one slot, but the emitter device has to ensure that its transfer is completed before the end of its GTS or the CFP.

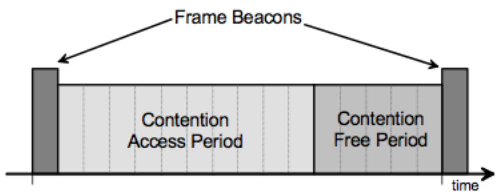


Figure 2.1: Superframe structure with GTSs

Further information and thorough details about the MAC layer and its frames and superframes possibilities and formats can be found at [11, p. 67].

Depending on the direction of the data flow and the usage of beacons or their absence, there are three modes of data transferring [11, p. 18], with additional variants according to the possible requirement of transfer acknowledgement. In the case of this project, whenever a emitter device has data to transfer, it listens the network waiting for a beacon and, once found, it synchronizes with the superframe, sending its information in its corresponding GTS. This process is illustrated in Figure 2.2 (notice that, in this particular case, acknowledgment is not employed).
Due to the possibility of entering low-power mode this standard provides during the lapse of CAP, it allows significant power saving. In Figure 2.3 and Figure 2.4 it can be seen that the Shimmer's power consumption significantly drops after the receiving of the beacon. Two and three clearly different phases, respectively, can be observed in both figures:

1. **Beacon Reception:** first part, which lasts 1.39ms and averages 72.39mW, corresponds to the radio entering reception mode when the beacon is expected. Second part consists of the beacon reception itself,

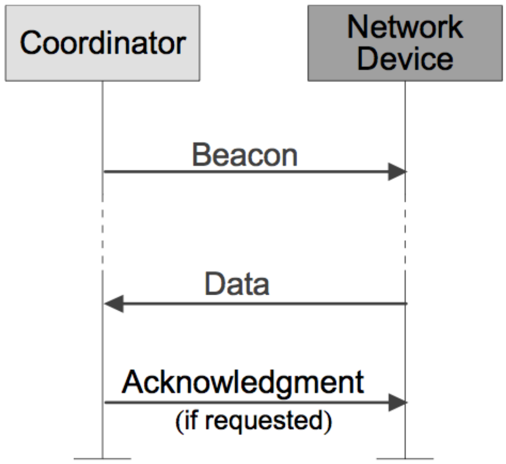


Figure 2.2: Communication to a coordinator in a beacon-enabled PAN

and it lasts 0.97ms and averages 82.59mW.

2. **Low-power mode:** the radio keeps its power consumption to a minimum until its GTS, if any packet is to be sent, or till the following beacon. In this stage, the consumption averages 6.6mW when both the microcontroller and the radio are idle, and 16.8mW when the microcontroller is active updating the tick counter.

3. **Packet transmission:** (only in Figure 2.4) first part is due to the sending of the package from the microcontroller to the radio chip, which is still idle (16.8mW, 2.85ms). Second part corresponds to the actual transmission of the packet, which averages 51.92mW for 4.51ms.

Oscillations, or peaks, can be observed during the entire process and are due to the continuous tick counter update (every 0.32ms) the operating system carries out. These results were obtained by measuring the voltage at a resistor which was specifically placed in the emitter node's power path, as it is detailed in [7, p. 860].

These low-power periods grant a much better battery life when compared to the one Bluetooh, as the wireless alternative Shimmer provides, allows because of the constant user and protocol data flow that it causes, fact that is aggravated by its much broader bandwitdth. Thus, it provokes that the average Shimmer battery life employing 802.15.4 is more than one order of

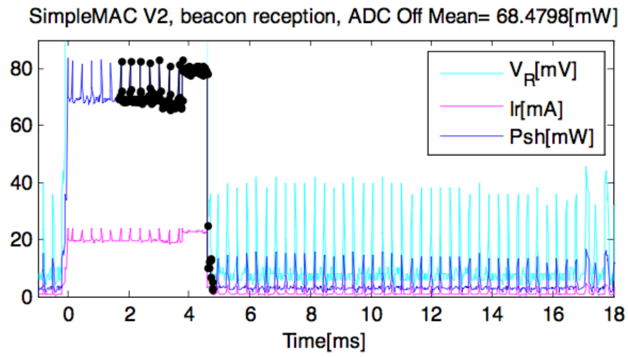


Figure 2.3: Shimmer power consumption analysis, beacon reception

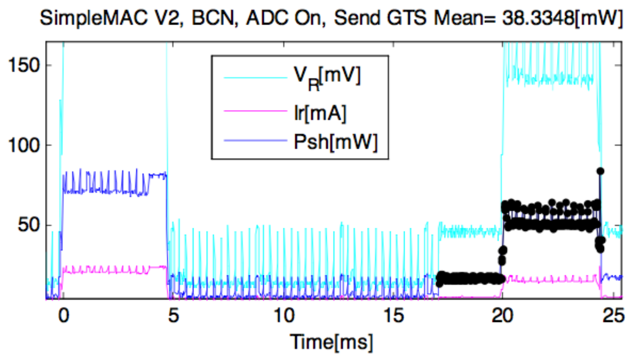


Figure 2.4: Shimmer power consumption analysis, beacon reception and data transmission

magnitude higher than employing Bluetooth. For instance, a fully loaded battery would increase its life from about 4 hours and a half to almost four days, which would be particularly interesting as it would let its replacement not to be a constant nuisance. These calculations come from a 280mAh Li-ion battery @ 3.7V powering the same Shimmer device sending the same data through Bluetooth (4.41h, 235mW) or 802.15.4 (89.17h, 11.63mW).

Particularly, using 802.15.4, in a period of almost 1 second (980ms), the reception of one beacon along with the sending of 7 packages takes place, which only lasts for 53.44ms. Thus, the device stays in low-power mode for all the time left, 926.56ms. In other words, power consumption is at its minimum for the 94.95% of the time, as opposed to Bluetooth, which always keeps it at its highest value.

2.3.5 FreeRTOS

FreeRTOS is a real-time operating system specifically designed for embedded devices, and has been ported to 31 different architectures hitherto. Due to its real-time nature, it features small sized binary images and memory footprint, real-time tasks and co-routines, as well as communication and synchronization tools for tasks and interrupts (queues, semaphores, mutexes). So as to achieve this real-time suitable condition, it is predominantly written in C and carefully coded in order to guarantee its portability and compatibility with different compilers.

This project makes use of FreeRTOS so that it manages the receiver device's resources and handles the data reception and beacon sending of its radio as well as the USB communication with the Android device. However, despite the self-claimed compatibility with MSP430 architecture, the official port of FreeRTOS was not compatible with the microcontrollers employed in this project (specified at subsection 2.3.2, MSP430) at the beginning because it did not support the newer members of the MSP430 microcontroller family (although it currently does).

Therefore, the operating system had to be accordingly modified and subsequently ported in order to support the target MSP430F5438A microcontroller. This task was carried out by one member of the department, and consisted of adding support for extra peripheral devices, such as radio, serial port, USB and clocks, and adapting the intern management of interrupts and routines of the system. This process has been conducted outside of the project scope.

2.3.6 USB device & USB host

USB host [25], as opposed to USB accessory, is an operation mode which determines how a USB-equipped device interacts with another one. The two connected devices are differently named according to the role they assume in a host or accessory mode connection, namely USB host and USB device. This designation is based on the role each device is playing rather than the sort it belongs to. In particular, one end is named USB host if its apparatus is responsible of supplying power to the one at the other end.

In relation to this project, the main difference between both modes lies within the direction the power supply follows or, more specifically, the role the Android running device adopts: Android device acts as host in USB host mode, whereas it acts as device in accessory mode. However, there is no difference in data transfer between them, as it remains bidirectional in both modes. It is typical for the device with larger power consumption (usually the Android device) to act as the USB host since it probably has a power source of any kind, although this is not always this way.

In addition, when a device acts in USB host mode, creating the connection, that is, instantiating and initializing the proper sockets, between both ends is its responsibility, along with notifying the other end about the establishment of the communication. On the other hand, the process that the device role assuming system has to carry out is quite simpler, as it just consists of checking the availability of the previously created communication.

Regarding this project, this matter applies in the way both the Android and the receiver devices are connected and which one assumes the USB host role. It would result particularly desirable that the Android device acted as host so that the receiver could be fed from its battery (which would make the collection really portable, non-dependent on the accessory power source). However, it depends on the specific platform that this arrangement can be possible.

Although certain Android devices running version 2.3 were capable of offering USB host support, this version only officially supports USB accessory mode; whereas USB host mode is only available by default since version 3.1. Thus, in order to get the required behaviour the usage of one of this special devices or, preferably, a device running a 3.1 Android version or newer.

2.4 Description

The hardware related investigation is the main section of the research part of the project. Not that there wasn't any research involved in other areas, but some critical elements of this part had never been researched before. At the beginning of the project specific objectives were established and main milestones elected, but absolutely no clue or direction for most of those milestones was available. Moreover, in some cases the feasibility of the proposed goals was unknown. Specifically the achievement of the very important objective of USB communication between an MSP430 and an Android powered device assuming the latter the role of master and acting the former as a slave was something not done before and therefore no information was available even in the Texas Instrument support site.

This whole development and research poses some quite interesting challenges as it involves working nearly at every abstraction layer present on device development, ranging from schematic capture and PCB design to operating system related development. The main issues to be resolved are:

- **802.15.4 radio reception:** data packets are emitted from the monitoring Shimmer^{TM}and are to be received and dealt by the accessory. In order to do so, FreeRTOS has to be equipped with a working implementation of the radio stack, which involves implementing part of ZigBee's MAC layer, described by IEEE 802.15.4, as it is the underlying standard which the emitter nodes are based on.

- **MSP430 USB handling:** just as the radio stack, FreeRTOS is not prepared to make use of the USB interface with which the MSP430 board –namely TS430PZ100USB– is equipped. Thus, it is necessary to add the essential code in order to incorporate this functionality to the OS. This issue, in the same way as the previous one, is a critical part for the system to work properly since it may likely be a source of errors unless it is perfectly made –for instance, it could add transmission lags, packet corruption or even full package losses–.

- **MSP430-Android communication:** this issue is particularly relevant as no project has ever claimed to feature this kind of connection before. Hence, it means an additional challenge to be overcome since it will involve the modification or complete development of an specific driver for the MSP430-equipped device. This challenge is imposed by choosing the USB host alternative so that the Android device powers the accessory. On the other hand, USB device may ease this issue due to the already resolved communication system with accessories made by Google, yet it implies the accessory will need an additional power source. Fortunately, it finally turned out not to be so tough as it was expected and the goals related to this issue were successfully fulfilled, as it can be read at subsection 2.5.2, MSP430 for Android USB Host Comunication.

Over the following lines within the next section, the aforementioned challenges are detailed in the context of their own development stages. In addition, objectives and results of each one of these stages are also presented.

2.5 Milestones

Due to the fair amount of time a essentially researching work like this hardware development requires, the foreseen schedule is subject to changes which may completely alter it regardless of how irrelevant they may seem, and thus avoid the success of the project.

Keeping this risk in mind, the hardware development is planned as a sequence of milestones, ordered by increasing complexity. Every milestone introduces a new technology, each one of them capable of covering the needs of the project in a more complete way. In other words, the previously presented issues are to be resolved as these stages are overcome.

The schedule, then, starts with the usage of the Google Open Accessory Development Kit, based on Arduino, in order to make a prototype as first approach and, in this way, be able to parallelize software and hardware development –notice that both of them depend on each other–. This choice is made because of the well-known soft learning curve Arduino presents as well as the already prepared connection the Google ADK provides between accessories and Android devices.

The next step in the development, once the application has been proven to communicate with a data-providing accessory, consists of making Android capable of detecting and communicate via USB with an MSP430-equipped device. This stage can be qualified as very critical, since almost every part of the development depends on it.

The following milestone arises as a consequence of the FreeRTOS port which was specified before: its target device, namely MSP430F5438A, does not support USB communication, and by extension the port itself. Thus, the work for this stage consists of providing FreeRTOS with USB support, which is to be employed with the new target device, MSP430F6638, which is member of the MSP430F66xx family with highest performance, along with USB support.

Next, the planning sets the development of the communication between the emitter nodes and the device. The previously existing FreeRTOS port already supports the IEEE 802.15.4 standard MAC layer, so the work in this milestone involves modifications in order to get the port to work properly with the new MSP430F6638 platform. Although the first versions of the schedule considered this next step at the same time of the previous one, in later revisions it was decided to keep them separated for the sake of the stability derived from isolating both developments.

Due to the division between the two previous stages, both developments, USB and radio stacks, are to be done separately. In order to resolve the likely communication problems this decision can cause, the next iteration the planning considers is reserved for validating and fixing their coexistence may provoke.

Finally, the schedule adds two extra stages: the first, which may be dropped due to eventualities, considers the design of a miniaturized version of the receiver device so as to dispense with the TS430PZ100USB board, which is rather big and little portable. The second one is essential as it is reserved for possible needed fixings and refinements.

All these stages are now detailed over the following subsections.

2.5.1 Arduino for Android USB Device Comunication

The objectives for this first milestone objectives are:

- acquire a suitable Android device prototyping environment,
- manage correct communication between Android and a prototype device, and
- develop an application emulating desired behaviour.

This milestone is set upon the consideration that it is a good approach in order to familiarize the team with communications between Android and USB devices. It also comes motivated by the previously supposed effort the connection between Android and an MSP430-equipped device involves, since it has not been done before as well as Android USB host mode support has been out for only two months.

The process involved in the procurement of each objective is exposed next.

1. *Acquire a suitable Android device prototyping environment*
   The first step in order to develop this USB device consists of looking for a platform which is able to provide the needed components and libraries so as to make the connection with Android feasible. Although several devices are available to serve as Android accessories (as it is explained at subsection 2.3.1), Google ADK is the chosen one since it is based on Arduino: a considerable amount of libraries and documentation is to be expected. Particularly, USB host mode library is the main reason for choosing it.

2. *Manage correct communication between Android and a prototype device*
   Once the target platform is chosen, the next step to be done consists of developing some test firmware for the Arduino as well as modifying consistently the Android application so that a proper communication between both devices can be established and proven. A period of learning and adaptation is required for the team to achieve this.

3. *Develop an application emulating desired behaviour*
   For this milestone to be fulfilled, it is required that the firmware developed for the Arduino can emulate the behaviour of an actual sample-receiving device. Thus, the microcontroller board is programmed in order that it sends formatted data as the Android application is expecting to receive. In this way, it is visually verifiable that the data transmission is performing properly.

Although Google refers its ADK as an accessory developing platform, it is noticeable that it is in fact used as a prototyping tool, and hence this development is not to be employed as a part of the final state of the system. As opposed to this, this stage of the project is considered as training transition to more technical developments to be engaged later.

2.5.2 MSP430 for Android USB Host Comunication

Objectives for this stage are:

- supply MSP430 with USB protocol application functionality,
- research Android USB protocol related functionality,
- make Android OS recognize MSP430 when plugged, and
- manage communication between Android and MSP430 via USB.

Due to the need of USB support, both the microcontroller and its board models are required to be as new as possible, since older models lack this feature. Therefore, the MSP430F6638 microcontroller as well as the MSP-TS430PZ100USB board are selected for this development, as it is explained at subsection 2.3.2, MSP430.

Prototyping with Arduino during the previous milestone constitutes the preparation for the development to be done in the present one. Yet, whereas Android and Google ADK are designed to interact with one another, Android is not prepared for supporting a device like an MSP430 out of the box. So, in order to communicate both devices, an API from Texas Instruments [26] is the only available tool, though it is designed for Windows OS.

Among all the contents the TI API includes, its examples result particularly useful for the project requirements. Concretely, examples about CDC (Communications Device Class) protocol set the needed basis to fulfill the objectives for this milestone. Nonetheless, several examples does not seem to function, not even in Windows, its target operating system. Thus, the next step consists of studying both the examples and documentation from TI so as to fulfill the objectives.

1. *Supply MSP430 with USB protocol application functionality*
   As it was previously said, TI API contains a huge amount of information in the shape of:

   - **Extense documentation:** about the API itself and features of TI devices.
   - **Sample Windows Applications:** made to communicate Windows PCs with external devices or enumeration tools.
   - **Suite of examples:** each of them implements a combination or one of the following USB protocols: Communications Device Class (CDC), Human Interface Device (HID) or Mass Storage Class (MSC).

   The same problems, though, keep these examples from working with the target MSP430 device. As a result of an intense investigation the trouble is found to lie within one of the device's clocks which, according to the API documentation, may need an specific tuning –particularly, 4MHz–. Moreover, in spite of the fact that the board seems functional, it actually lacks that certain clock. As expected, TI example properly works with the addition of the 4MHz clock.

In addition to the previous hitch, another one arises upon changing the current workstation. Every work during this development is carried out within a Windows virtual machine running over Windows, yet the examples stops working when the host machine is changed for another one running GNU/Linux, particularly Ubuntu. Despite having achieved the present objective, this fact reduces the expectations for the next one since Android, the target OS, is also based on Linux kernel.

2. *Research Android USB protocol related functionality*
   As it is expected because of its performance with Ubuntu, Android is not able to recognize the target device, and hence the example cannot be tested. In order to solve this inconvenience, two solutions are considered: search for the proper driver, if any, and modify it or develop it from scratch.

   Nevertheless, the search concludes with no results, so it is assumed that this particular driver does not exist. The most similar resource found consists of a driver for MAC OS X, which would have to be consistently modified in order to make it work. However, this idea is dropped due to the advice obtained from a qualified source that suggests exploring other methods to make the communication feasible apart from developing a driver, which may be too harsh and require too much time. A quite considerable risk is assumed by doing so as there are no warranties of finding a proper solution.

   Fortunately, further research drives to a successful alternative: it is found that Android actually implements HID protocol, which is also supported by MSP430 through the Texas Instruments API. Finally, upon loading the proper HID application into the MSP430 from the TI API this objective reaches its fulfillment.

3. *Make Android OS recognize MSP430 when plugged*
   Once both two first objectives of this milestone are achieved, MSP430

recognition by Android is inmediate when the connection is set since all the needed work is already done.

4. *Manage communication between Android and MSP430 via USB*
At this point, the work still to be done consist of modifying the Android application in order that it can read data from the receiver device. However, this is not a trivial work as Android USB host communication is highly dependant on the device which it has to read from. Thorough investigation over the API manuals is required to discover every detail and make it work.

Therefore, as it can be deduced from the previously explained happenings, this stage draws a great amount of risk to the hardware development due to several critical points it involves which further required tasks are to be based on. In other words, part of this project's probabilities of success greatly depends on the feasibily of the present objectives, so this milestone completely conditions the planning. Once it is finished, it certainly allows to tune the schedule with better accuracy.

2.5.3 USB in FreeRTOS

This milestone's objectives are:

- check the proper working of FreeRTOS with the new microcontroller,
- validate the feasibility of the usage of USB API along with FreeRTOS in MSP430,
- correctly integrate USB API into FreeRTOS, and
- manage USB data sending in FreeRTOS.

Despite having already achieved communication between Android and an MSP430 device through USB, there is still work about this since it is only a test version which does not take FreeRTOS into account. In fact, FreeRTOS, as it is explained at subsection 2.3.5, will be responsible of managing the operation of the microcontroller in addition to the radio. So, adapting the USB functionality and equipping FreeRTOS with it arises as the next relevant stage of the project, required to make the receiver device possible.

1. *Check the proper working of FreeRTOS with the new microcontroller*
   Prior to starting with this milestone's core objective, FreeRTOS needs to be adapted in order to make it work with the new microcontroller, namely MSP430F6638, since it is addressed to a different model, the MSP430F5438A. This change implies the modification at several points of the code of the operating system so that its proper working can be assured.

2. *Validate the feasibility of the usage of USB API along with FreeRTOS in MSP430*
   The following objective to be achieved consists on incorporating the TI USB API to FreeRTOS, focusing in its completion rather than its perfect working. This is not a trivial task due to the large extension of API's code. Furthermore, The most relevant inconvenience that endangers this work is the considerable amount of resources which are found to be in mutually exclusive condition, such as microcontroller pins and clocks. However, this is a matter of properly balancing the distribution of these resources over time, and thus it can be achieved by paying special attention and care to it.

3. *Correctly integrate USB API into FreeRTOS*
   Although the USB API is already functional and integrated into FreeRTOS, this integration is made without caring about keeping the compatibility with already supported microcontrollers, and hence losing this feature. Therefore, the next step consists of restoring its support for other devices like MSP430F5438A. Nonetheless, as the original FreeRTOS port already supported different devices such as the one mentioned and Shimmer$^{\text{TM}}$, this work is not as hard as it should be if carried out analogously.

4. *Manage USB data sending in FreeRTOS*
   Once the USB functionality is properly integrated into FreeRTOS, it is required to check whether the communication it provides correctly stablishes and the trasmitted data does not suffer from corruption or loss. The method used to test this consists of running a special program on FreeRTOS which sends a known character sequence so the input and output sequence can be checked as equal. As they are, in

fact, the same sequence, this objetive along with the entire milestone are fulfilled.

With the work carried out during this stage, communication between the receiver and the Android device is completed, fact that limits the work that is left to to the management of the wireless reception through 802.15.4. Wireless communication will be dealt over the following two milestones.

2.5.4 802.15.4 in FreeRTOS

This milestone's objectives are:

- validate current implementation of 802.15.4 in FreeRTOS on the MSP430 testing board,
- manage connection to the CC2420 radio module to the target MSP430 device,
- port implementation of 802.15.4 to the target MSP430 device, and
- prepare such implementation for actual usage.

The next step is the achievement of wireless 802.15.4 receiving in the MSP430 board through the CC2420 radio module. An existing port of the MAC layer for the FreeRTOS running in the MSP430 is taken as the starting point. The main advantage of employing it is that it's the same code running in the 802.15.4 emitter utilized in the project. In any case, before actual usage a correct validation of the software is mandatory. Once validation is completed, the MAC layer is to be implemented into the target MSP430 device and tweaked for actual usage. That is the ultimate goal of this milestone.

1. *Validate current implementation of 802.15.4 in FreeRTOS on the MSP430 testing board*

   Before addressing the delicate task of implementing the 802.15.4 MAC layer port into the target MSP430 device, validation of this port is conducted in the testing MSP430F5438A board. This decision is motivated by the fact that this board provides serial port output and out of the box CC2420 connection.

The testing of the MAC layer provides negative results, as although 802.15.4 receiving functionality is present in the port, the OS is not actually notified about it and the received data is lost. Moreover, problems in the receiving of packages of maximum size, which are the ones sent by the 802.15.4 emissor, are also detected.

The amendment of the aforementioned problems takes no longer that expected, and the porting of the 802.15.4 support to the target MSP430 device begins. The original developer of both the FreeRTOS port and the MAC layer is notified about the detected problems, and the fixes are also implemented on the 802.15.4 emissor.

2. *Manage connection to the CC2420 radio module to the target MSP430 device*

   The target MSP430PZ100USB board provides no CC2420 radio module connection socket, so the port of the validated 802.15.4 module to this board requires manual connection handling of the radio device. The MSP430 features a 100-pin footprint, and a complete study of all the 100 pins target usage and on-board availability becomes mandatory for the identification of the pins that the CC2420 will be connected to. Special care is put to avoid collisions between the USB and the radio modules regarding hardware resources.

   Successful identification of the required pins done, a manual soldering of the CC2420 radio module is executed and subsequent testing can continue.

3. *Port implementation of 802.15.4 to target MSP430 device*

   The inclusion of the 802.15.4 MAC layer into the target MSP430 device involves modifing the FreeRTOS pin mapping code, which is a specially sensitive task. The code is carefully modified taking the mapping code for the already tested MSP430F5438A as the base. Special care is put in the task as any mistake would cause the radio module to fail at initialization and following error tracking would be very time consuming.

Once the FreeRTOS pin mapping is complete, no further work is, initally, required in the port process.

4. *Prepare 802.15.4 implementation for actual usage*

   Having both the hardware and the software part of the 802.15.4 module port completed, actual testing is conducted on the target MSP430 device, resulting in an initial absolute failure. The radio module nor even turning on, an in-depth research on the subject becomes the main priority.

   The solution is found in one of the TI code examples for the target MSP430, which provides a different code for the Universal Receiver/Transmitter (USART) initialization routine than the one employed in the testing MSP430F5438A. Substitution of this code in the FreeRTOS implementation solves the problem and further testing indicates that the radio module implementation has concluded.

The rest of the milestone allotted time is then employed in final test conducting resulting in small changes to the code to fully adapt it for the project needs but no critical changes are required. By the end of the milestone time a fully functional 802.15.4 module is achieved in the target MSP430 device, although actual validation of the correct coexistence of the radio and USB modules is to be conducted in the next project phase.

2.5.5 802.15.4 & USB coexistence under FreeRTOS

This milestone's objectives are:

- assess conflict-free coexistence of current implementation of both USB and 802.15.4 modules in MSP430, and
- manage sending data received from 802.15.4 via USB.

Having both the USB communication and the 802.15.4 receiving working over FreeRTOS when isolated, the next task assumed is the testing of them both working together. While they should theoretically coexist without conflicts, the manual mapping of the processor pins performed in the last milestone involves a risk this won't happen. Once such hardware validation has concluded, software validation is also to be conducted by the development of a first version of the USB sending program.

1. *Assess conflict-free coexistence of current implementation of both USB and 802.15.4 modules in MSP430*

   As said, resource sharing conflicts are bound to occur when joining the radio and the USB modules. The possibility of hardware related conflicts being known when developing each module, special care is put in the selection of resources for them both. The testing conducted in this phase confirms the successful outcome of these task, as no real hardware conflicts arise.

   For software conflict testing the decision is made to validate directly against an actual application featuring part of the functionality required in the final receiver. That testing process is then merged with the work required for the next milestone objective.

2. *Manage sending data received from 802.15.4 via USB*

   For the achievement of this objective, an application is developed with functionality to send the byte sequences received from the CC2420 radio module via USB employing the HID protocol. Software resources sharing between both modules is confirmed to be conflict-free, concluding the validation of the correct coexistence of them both, yet a specific problem is found to occur.

   The real-time sending speed of the 802.15.4 emissor and the limited storage capacity of the CC2420 radio module, as well as delays caused in the processing involved in USB data sending, are found to be causing the loss of data packages. The solution is twofold: on one hand, and regarding the 802.15.4 emissor device, the package emission is stretched to employ the whole available time slot, instead of sending all the data as fast as possible at the beginning. On the other hand, a buffering system is implemented in the receiver device to allow the constant processing of arrived data when a package is currently being sent via USB.

The described solution removes the problem and the objective is, thus, accomplished. Moreover, full required functionality for the receiver device is implemented.

Before the finalization of the milestone some final testing is conducted with positive results. The 802.15.4 receiver device is capable of sending data received form the radio following the 802.15.4 standard through the USB connection. This allows the beginning of actual accessory development with the objective of obtaining a small PCB, closer to an actual product than the MSP430 equipped board.

2.5.6 MSP430 based device design

The objectives for this milestone are:

- exhaustive analysis of the reference board,
- capture of the board schematic, and
- design and routing of the actual PCB.

At this point the objective of the hardware research part of the project has already been achieved. An MSP430 based 802.15.4 USB receiver has been developed and tested. It is able to connect to an Android device and draw power from it, and little power is required. Low power requirements achieved, the next step is the miniaturization of the board so as to minimize the size of the system. Production of a small device which can be attached to the Android system is the objective of this milestone.

1. *Exhaustive analysis of the reference board*

   The device board design is to be made taking the MSP-TS430PZ100USB board as a base, as it provides all the components required by the target device and the schematics are available as part of the official Texas Intruments provided documentation. The first step towards the achievement of the low sized device is the correct identification of the minimum set of components required by the target functionality, as not every component present in the base board is actually used. This is so because the TS430PZ100USB is an evaluation board providing a lot of features targeting the simplicity of the prototyping process.

In order to minimize the size of the board, three main modifications are conducted. First, power source selection related circuitry is removed and the board is left with just the ability to get power from the USB connection. This eliminates a number of power source selection jumpers and voltage regulation components. Second, a meticulous selection of the processor pins which will be available for external usage is performed. This selection tries to balance between minimizing the number of pins exposed and as featuring as much expansion capabilities as possible. The final set includes, apart from the pins required by the radio and USB modules as well as power related ones, the eight pins required for one of the IO ports, one pin intended for the connection of a led and one for the inclusion of a reset switch.

The other main change to the original board is the inclusion of the connection sockets for the CC2420 and the substitution of the debugging JTAG port for a smaller one, which will require the production of a standard JTAG cable adaptor but will also reduce the size of the board significantly.

Once the selection of components is validated, the production of the schematic of the new board begins.

2. *Capture of the board schematic*

The design of the board schematic is the next step towards the obtention of the actual PCB for the device. The schematic capture process is done from scratch, even if the board is based on the TS430PZ100USB, because no usable schematic file for the evaluation board is found. The device circuitry being simple, the main problem source for this task is the selection of as small as possible footprints for the board components, and further implementation into the design software. Some of these footprints are obtained from trusted sources, and other, more obscure ones, are to be made by hand. This footprint selection process is very important, as will be the foundation of the PCB design stage.

Once the schematic is finished and validated, a first prototype is to be built for actual testing. Prior to this, the development of the bill of materials of the device is performed, focusing in minimizing the total cost while acquiring the as small as possible, specifically choosen footprint featuring componets.

3. *Design and routing of the actual PCB*

In order to start the design of the miniaturized receiver, validation of the proper operation of the developed prototype is mandatory. As it can be expected, minor mistakes may be made in both the schematic capture and the prototype building which may make the final product does not work once built. In fact, avoiding such kind of failures is the purpose of the prototype.

Once the test of the prototype is completed, the designing process just consists of finding a proper location for each one of the previously identified components. This task entails several risks since the design is subject to changes, changes which, however small they are, may lead to a complete redesign of the device. Hence, special care has to be devoted to this job so as to avoid significant waste of time.

As for the PCB routing, special attention has to be paid so that the actual routing is as similar as possible to the planned one, and hence less time is to be dedicated to the correction of the circuit tracks. In addition, assuring each component has enough space, tracks are not overlapped and power lines are wide enough to guarantee the correct voltage are also critical tasks.

Assuming this guidelines are followed, PCB routing becomes feasible and gets done with no additional problems, so the building of the device is ordered.

In the absence of a thorough testing of this miniaturized version of the receiver device, which is set to be done during the next stage of the project, the miniaturization process is successful and a significantly smaller version is obtained. In particular, its dimensions are 61 x 32 x 6 mm without antenna, 61 x 32 x 35 mm with antenna, as opposed to the measures of the prototype 72.5 x 63.5 x 35 mm and the training board, considerably larger. These smaller dimensions play a determinant role both in the adoption and usefulness of the device.

2.5.7 Final Validation and Release Candidate Version

The following tasks are to be completed within this last stage of the development:

- Validate the final version of the receiver device, and
- fix possible errors.

Tests are to be driven with the recently built receiver device in order to assure its proper operation, capability of being programmed as well as its correct behaviour when carrying out its tasks within the whole system. Due to the thorough previous tests and revisions its design and its predecessors (both the training board and the mockup) have passed, little or no bugs are expected to be found. Even though, this task is focused on checking so as to avoid unexpected behaviours or malfunction with the last version of the receiver.

Fortunately, thanks to the meticulous process that has been conducted to avoid unforeseen failures, the final device works flawlessly, except for few minor fixes quickly resolved.

2.6 Closure

The hardware part of the project has successfuly achieved the objective of the production of an 802.15.4 USB receiver. This device provides all expected functionality, specifically the transferring of data received from the

802.15.4 radio module via USB acting as the slave device in the USB connection, drawing its power from the master device. This master device can be any system with an implementation of the HID protocol, and the produced device has been tested as an 802.15.4 receiver both for an Android device and a Windows based computer. Moreover, taking an evaluation board as the starting point, the device has been custom designed and produced, and miniaturization has been conducted so as to be built into a printed circuit board, even if actual production of such PCB has been initialized but not yet finished.

The fact that the 802.15.4 USB receiver is independent from the domain of the project, i.e. it only assumes the task of sending through an USB connection the data received through the radio, it does not analyize or processes the data, makes it a fully functional general purpose 802.15.4 receiver. Functionality for data sending through 802.15.4 is present in the device, both in the software and hardware layers, but it lacks the code to send data received from USB to the radio. Nevertheless, this functionality can be implemented with ease, thus turning the device in a full fledged 802.15.4 USB emitter/receiver.

In the specific scope of the project, the application of the device for the receiving of the ECG wave data, due to its small size and low battery requirements, leads to a more comfortable employment of the monitoring system. Even if the necessity of employing an Android accessory decreases the portability of the system when compared to the utilization of the Bluetooth module, which is embedded in the Android device, the order of magnitude lower battery requirements compensate throughout, as the lifetime of the battery of the ECG delineator node when using 802.15.4 is increased from hours to days.

In conclusion, all the objectives of the hardware research and production have been achieved in the deadlines set for the project, even when coping with the uncertainty inherent to any research and sharing resources with the parallel-conducted software development. Moreover, additional objectives has been pursued and also realized, like the development and miniaturization of the custom board, making this hardware project a success.

Chapter 3

Software Development

3.1 Introduction

The development of a software ECG display application targeted at Android Operating System for mobile devices is the counter-part to the hardware research part of the project. This application is to substitute the already developed one for iOS devices, adding funcionality extracted from feedback obtained for that and including extra features which could not be implemented in it. The software must provide functionality to visualize ECG data from Bluetooth or 802.15.4 sources (the latter obtained via the 802.15.4 USB receiver developed in the hardware part of this project) in real-time, as well as to save that data into file logs for afterwards reading.

Android as a development platform provides a wide set of high abstraction level tools to emphasize robust and reusable design for low resource based, quick development cycles. Such benefits require the adequation of the software design and architecture to the constrains imposed by the Android development framework.

Given that none of the project team members had received any instruction on this framework, engaging the development of an Android application implies an important risk. Moreover, after the research and training steps concluded, follow up of such risk can not be halted, as the quick, robust software development is only assured when building an standard Android application; dynamic, soft real-time functionality implementation is not discouraged, but also not guaranteed to work. Mobile devices development restrictions and common practices are also unknown to the team at the beginning of the project.

Even when the aforementioned eased development features are applicable, mobile devices are harsh software environments due to, amongst others, memory and battery constrains, where processes have to handle being suspended by an incoming call or similar external events. This factors are specially critical for an application as the one developed in this project, which needs to continually parse and log data.

The application is also intended to act as a quick testing front-end for the prototypes produced by the parallel-conducted hardware research. By providing fully-functional application modules since early stages of development, hardware prototypes could be best-case and worst-case checked by directly connecting them to the Android device for data visualization. Throughout the project process, visual verification has proven to be a very effective method when working with large quantities of data which were more easily checked against their visual representation than value-by-value reading.

These factors lead to the adoption of an agile software development process focusing on functionality building while prototyping more high risk involving features. To avoid typical drawbacks of such methodologies, great emphasis is put on the application of characteristics found in *Iterative and Incremental processes*, namely, use case driven and risk focused development. That way, project scheduling is done addressing higher risks first while assuring expected functionality to be implemented on time thanks to the use case model.

3.2 Overview

In the following sections a complete view of the software development project is presented, beginning with the requirements captured for the project and a comprehensive description of the risk analysis process. The use case scenarios identified from the requisites will be detailed next, followed by an explanation of the system design and architecture. Then, the development process will be exposed in an exhaustive manner, and the chapter will finish with a review of the software development project.

3.3 Requirements

The requirement capture process for the project considers three main stakeholders: the project directors, the EPFL and the UCM as the base project developer parties and the project team members; and is done in two sessions. The first one produces the basic requirement list which describes the system and is used to schedule the earlier development iterations. This is so because of the strong time restrictions this software development project had to cope with. When the critical functionality is achieved and the hardware research reaches a suitable state, the second requirement capture session is conducted. By then, the EPFL and UCM representative had shown the state of the development to the stakeholder party of him, and collected feedback. Thus, the requirements produced by this second session are of a more user-oriented nature.

The functional and non-functional requirement lists are presented next.

3.3.1 Functional Requirements

- R01 - Receive raw data via Bluetooth
- R02 - Receive raw data via 802.15.4
- R03 - Receive raw data from a log file
- R04 - Parse raw data into processed data
- R05 - Display processed data
- R06 - Log raw data
- R07 - Log processed data
- R08 - Scale View Vertically
- R09 - Scroll View Vertically
- R10 - Scroll View Horizontally

3.3.2 Non-functional Requirements

The following non-functional requirements are identified:

- The application must display ECG data at 30fps.
- The application must run on a Motorola Xoom device.

3.4 Risk Analysis

Being the project mainly a hardware research project, and considering the software development part of it useless without successful results on the hardware part, a detailed process of risk analysis is mandatory to be conducted since the earlier stages of planning and development so as to avoid wasting manpower on futile work.

The risk list at the end of the project is as follows:

- **PR1.** Functionality of the application is inferior to that featured by existing iOS application
- **HR1.** 802.15.4 receiver device delayed
- **HR2.** 802.15.4 receiver device unfeasible
- **MR1.** Mobile device unsuitable for target functionality
- **AR1.** Lack of instruction on Android development delays workflow
- **AR2.** Android providing subpar performance when handling required data
- **AR3.** Android rendering capabilities unable to handle required data

This risk analysis focuses on two main risk sources: the parallel-conducted hardware research, and Android as a development platform. Project definition and team related risks are also considered.

The hardware research part of the project delivers the highest probability and impact rated risks. It is so because those risks are external to the software development project scope and thus can not be handled by any of the tools provided by any development methodology. At the same time, should such risks come to be, the impact on the software product would be, in most of cases, as catastrophic as turning the whole development useless thus causing its cancellation.

Regarding Android development only a subset of the final set of risks is assessed at first. Every risk in this subset dealt with the team lack of knowledge about the Android platform and was scheduled to be addressed foremost. A last risk is added to this group after the first research on mobile devices limitations regarding potential unfitness of such devices for near real-time display and handling of not-so-small data packages. That risk handling plan proves to be key to the successful outcome of the project as the remaining subset of Android-related risks are linked to Android applications display performance.

The usual project definition and personal risks such as incorrect deadline scheduling or unability to reach critical milestones on time are also pondered, increasing their impact rates as the application would be needed by the hardware device to secure a successful outcome for the project.

A detailed view of each assessed risk is provided next, including risk evolution throughout the project lifetime.

PR1. Functionality of the application is inferior to that featured by existing iOS application
Probability: Moderate
Impact: Very High
Description: Failure to provide an expanded set of features in the Android application when compared with the iOS application renders the software part of the project invalid on its own. It could, then, only be valid as demo software for USB receiver device showcasing. If the device is not finished, then the whole software development project will have been futile. The key marker for this risk is unability to generate valid software modules throughout the development that provide required functionality. Failure to reach milestones and use case realizations on time is other important marker. Preventive measures are taken to avoid the occurence of this risk since the beginning of the development by a functionality building focused project scheduling for the first development phases.
This risk is marked as surpassed at the reviewing meeting of Iteration 2 as all key functionality has been implemented, as planned.

HR1. 802.15.4 receiver device delayed
Probability: High
Impact: High
Description: Being the production of the 802.15.4 receiver device dependent on the hardware research part of the project a delay on the estimated milestones for that part of the project is likely to occur. Should that happen, hardware research and development will need to be prioritized over

this software project. That could lead to big delays in software production. To prevent the rising of further problems derived from those potential delays, the software development process must always work with non-solid, ready-to-change deadlines and milestones. Application functionality is to be ranked in order of importance of implementation to be prepared, in case of an unexpectedly big delay, to leave less important functionality out of the scope of the project. Markers to be followed up are: unsuccessful output from hardware research (a new branch of the potential technologies tree has to be explored), failure to reach hardware development or research milestones and delays in the acquisition of tools or devices needed for the hardware project. Preventive measures considered are: detailed follow up of the hardware research development, reducing the software development team if manpower is needed in the hardware area, and planning asuming delays on component acquisition.
HR1 is monitored throughout the whole software development project, and marked as surpassed at the reviewing meeting of Iteration 5.

HR2. 802.15.4 receiver device unfeasibe
Probability: Medium
Impact: Critical
Description: Until hardware research results are successfully delivered there is no guarantee of the viability of the 802.15.4 receiver device. This software development project loses most of its value if such device is not developed, as the iOS application already exists. Developing an Android application with an equal feature set is also a valid objective, so this risk does not render the development invalid: the full team will then work on software development, and requirements will be restated to include more final-user oriented functionality and/or features from the *future* set. This risk can be monitored with the following markers: unsuccessful output from hardware research and failure to reach hardware development or research milestones. Being both external to this software project, no preventive measures can be applied apart from scheduling allowing smaller team sizes for the software area.
The probability of the risk is reduced to low after the reviewing meeting for Iteration 3, when the critical hardware research has concluded with positive results. HR2 is marked as surpassed when the production of a device prototype is finished and tested.

MR1. Mobile device unsuitable for target functionality
Probability: Low
Impact: Critical
Description: Even when mobile devices technical specifications have increased significantly in the previous years, specially regarding CPU power and rendering capabilities, the soft real-time requirements of the project in terms of data manipulation and visual representation involve a low probability risk of the application being unsuitable for such devices. The risk probability is decreased by the fact that similar featured applications exist both for iOS and Android powered devices. Even so, the 802.15.4 receiver device USB interface does not allow for this risk not to be reckoned. Preventive measures considered: quick prototyping of critical functionality to discard unfeasibility, conduction of performance tests, both rendering and data handling related, in the target device and testing of USB-Android communication as soon as possible in the project schedule.
As performance tests are conducted on early builds of the application, the need of further research on this risk arises as the data handling performance in the target device is low, but not as low as the rendering performance. Thus, this risk is unfolded into risks AR2 and AR3, both related to Android performance when handling the aforementioned tasks. This risk follow up is then halted, as it is no longer needed.

AR1. Lack of instruction on Android development delays workflow
Probability: High
Impact: Moderate
Description: None of the team members has received any instruction on Android development and throughout research is not viable because of time restrictions. It is reasonable to foresee potential delays in the development because of the parallel instruction-development flow, as well as the need to rewrite parts of the system rendered obsolete when further knowledge is acquired. Application malfunctioning, unexpected behaviours and low performance are markers to be tracked. As a preventive measure a short instruction time will be scheduled at the beginning of the project, but every team member is responsible to continue his instruction throughout the whole project. Application builds are to be checked for big differences against canon Android applications behaviour.
The risk is marked as surpassed after Iteration 3, as critical functionality has already been implemented and tested, though An-

droid instruction is not halted.

AR2. Android providing subpar performance when handling required data
Probability: Moderate
Impact: High
Description: The benefits of the high-level, single application model provided by Android are such in behalf of the sacrifice of performance. In this project soft real-time requirements are present, and the system needs to process around 250 ECG wave samples [7] (among other data) per second. Android code reutilization and class based programming suggested practices, the absence of an explicit memory management API and the employment of the Garbage Collector only complicate the achievement of such requirements. Special care will need to be put on the development and performance checks are to be conducted regularly on generated builds to ensure the avoidance of this risk. If evidence is found of Android inability to provide the required perfomance (and there is no way of attributing the failure to the team's lack of ability), low-level Android development will be considered. As the probability of this last scenario to occur is quite low, no research will be conducted in low-level Android development until mandatory.
The risk is verified to be happening during Iteration 2 testing phase. Lack of care on memory management is found to be the problem, and is solved in Iteration 3. The risk is marked as surpassed after the review meeting for Iteration 4.

AR3. Android rendering capabilities unable to handle required data
Probability: Low
Impact: High
Description: The Android Operating System runs on quite a wide range of devices, each with its own technical specifications. Providing the single application development model that Android features requires many software layers, many of them of high abstaction level. The risk exists, thus, that the rendering required by the project could not be achieved within the involved time restrictions. The target device for the project is fixed (see section 3.3 Non-functional Requirements Subsection) as a Motorola Xoom. This device employs a dedicated Tegra2 GPU [27] which should suffice, so risk probability is chosen as *low*. Performance tests in the display module are to be conducted, though, so as to make sure that a correct usage of the available resources is being done. If low rendering performance is detected,

Android native level rendering API, Renderscript, is to be looked into as a remedy, once the code is assured to be optimized.
Risk probability is increased to *Moderate* during Iteration 3 as low performance is detected but is considered not critical enough to apply the Renderscript solution. The risk is marked as surpassed in the reviewing meeting of Iteration 4.

Thanks to this risk analysis the project schedule is developed in such a manner that it prioritizes risk suppressing and the decision is made to plan only the first two of the five intended development iterations, leaving the other three as drafts to allow them to evolve at par with the uncancelled risks. Use case realization order is also selected based on this risk analysis, ensuring that higher risk involving features are developed (or at least prototyped) as early as possible.

Use cases for the project are presented next, followed by the system architecture description, to allow a finer understanding of the software development project schedule and related decisions, which will be detailed in the next section.

3.5 Use Cases

The project use cases are now presented following the *use case common style* described by Martin Fowler [Fowler, 2004], as the relaxed template allows for quicker document producing than more detailed descriptions such as those presented by Cockburn [Cockburn, 2001].

Actor listing is omitted in all the descriptions, because of the following implicits:

- The main actor for the use case is the user
- The only other actor is the data emitter node, when applicable. It can refer to the Bluetooth emitter device or the USB 802.15.4 receiver device.

Please note that the 802.15.4 emitter node is not considered an actor as the communication with such device is handled by the USB 802.15.4 receiver, which actually is the considered actor.

3.5.1 UC1. View data from Bluetooth

Description The user wish to receive and visualize data from a Bluetooth ECG node in real-time. He will start the communication, visualize real-time received data and finish the connection once done.

This use case captures requisites R01, R04, R05, R06, and R07.

Preconditions The application is in the main menu screen.

Main flow

1. User indicates his will to start Bluetooth data visualization.
2. The system prompts for the node to connect to.
3. User specifies the desired node.
4. The system manages connection to the node. If unable to establish the connection, see AF1.
5. The Bluetooth node sends data to the system.
6. The system shows processed data to the user. Received data is also logged.
7. The user can now adjust view parameters (See UC4)
8. User chooses to finish data visualization.
9. The system closes active connections and stops data visualization.
10. The system returns to the main menu.

Alternative Flow 1 The system cannot establish connection to the Bluetooth node selected by the user.

1. The system notifies the user about the problem.
2. The system returns to the main menu.

3.5.2 UC2. View data from USB Receiver

Description The user wish to receive and visualize data from an 802.15.4 ECG node in real-time. He will start the communication, visualize real-time received data and finish the connection once done. The data from the node will be received via the USB 802.15.4 receiver device.

This use case captures requisites R02, R04, R05, R06, and R07.

Preconditions The application is in the main menu screen.

Main flow

1. User indicates his will to start USB receiver data visualization.
2. The system asks the user to connect the USB receiver.
3. User connects the USB receiver.
4. The system manages connection to the USB receiver. If unable to establish the connection, see AF1.
5. The USB receiver device sends data to the system.
6. The system shows processed data to the user. Received data is also logged.
7. User can now adjust view parameters (See UC4)
8. User chooses to finish data visualization.
9. The system closes active connections and stops data visualization.
10. The system returns to the main menu.

Alternative Flow 1 The system cannot establish connection to the USB receiver device.

1. The system notifies the user about the problem.
2. The system returns to the main menu.

3.5.3 UC3. View data from log file

Description The user wishes to read a log file created from a real-time visualization session. He will specify the log file to load, visualize stored data and finish visualization once done.

This use case captures requisites R03, R04 and R05.

Preconditions The application is in the main menu screen.

Main flow

1. User indicates his will to start log data visualization.
2. The system prompts for the log file to load.
3. User specifies the desired file.
4. The system reads the selected log file.
5. The system shows logged data to the user.
6. User can now adjust view parameters (See UC4)
7. User chooses to finish data visualization.
8. The system stops data visualization.
9. The system returns to the file selection menu.
10. User selects to return to main menu. Else follow from step 3.
11. The system returns to the main menu.

3.5.4 UC4. Adjust view parameters

Description When visualizing ECG data the user wishes to adjust view parameters such as plot vertical scale, plot vertical scroll and plot horizontal scroll.

This use case captures requisites R08, R09, R10.

Preconditions The application is displaying ECG data.

Main flow

1. User indicates his will to change the vertical scale.
2. The system updates plot vertical scale.
3. User indicates his will to change plot vertical scroll.
4. The system updates plot vertical scroll.
5. If the displayed data is read from a log file, see AF1.

Alternate Flow 1 The user is able to control horizontal scroll parameter.

1. User indicates his will to change the horizontal scroll.
2. The system updates plot horizontal scroll.

3.6 Design and Architecture

The design of the software application is done targeting easy extension of the functionality which allows an incremental realization of the identified use cases and quick, isolated prototyping of new features in a manner in which already developed ones are not afected.

The Android Software Development Kit being the base technology employed in the development, the Android Application Framework conditions the basic architecture of the system. Particularly this framework imposes the utilization of a derivate of the Activity class as the entry point for the application. The idea is that an application is composed of various Activities, providing each of them “a screen with which users can interact in order to do something” [28].

The correct usage of the activities model in the Android framework includes declaration of them in the application manifest (see [28] for reference) and a number of other steps which are excessively formal for the target comfort and speed-of-operation levels regarding development of extensions. Specifically the application gives support for a number of data sources, namely Bluetooth, log file and USB device, each one with its own needs in terms of user interfaces and interaction. Moreover, new data sources would possibly require different interfaces than those already developed.

In such an scenario the decision is made for the architecture of the application to override Android activities model, employing only a single Activity which will implement a stack of user interfaces each with its own logic and behaviour, in the same manner Android does with the activities but allowing more flexible development. The inclusion of a new interface or set of interfaces is, thus, simplified, and every application entity is given the ability to present its own menu to the user. This is specially useful when including new data sources with special interface requirements to the application.

An overview of the application architecture is presented in Figure 3.1.

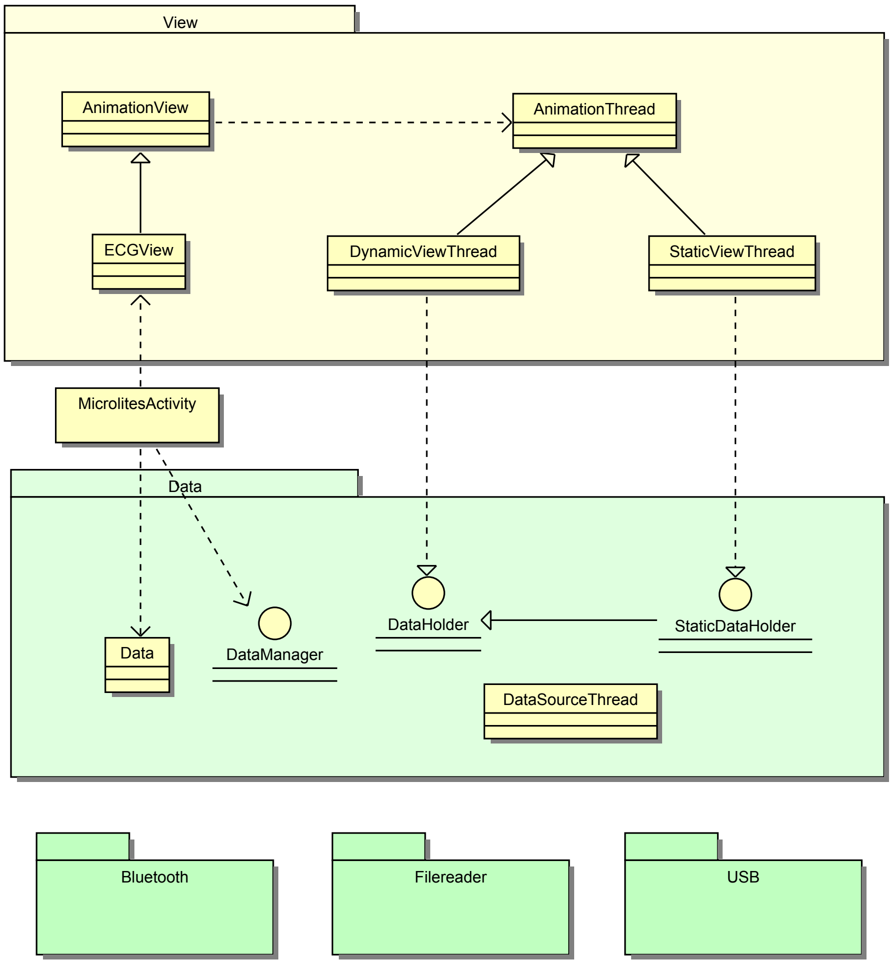


Figure 3.1: Architecture overview

At the core level the main Activity, the View package and the Data package are present, as well as three packages (Bluetooth, Filereader, USB) which will be dealt with later. These components provide the basic elements which compose the model over which actual functionality is built, and are to be seen as the tools available for the overlaying software layer which is addressed next.

The main Activity of the application assumes the role of the central coordinator and is responsible for creation and management of area specific managers, application level data and handling of the aforementioned user interfaces stack. It is also responsible, as the entry point of the application, of the presentation and behaviour management of the main application menu which gives access to actual functionality, delegating in the specific managers.

Of all those tasks, the most important are the initialization and eventual finalization of data visualization flows in collaboration with the appropiate area specific manager. Throughout the process, mainly controlled by the activity, components required for the visualization process are initialized, delegating area specific tasks to the manager. Eventually, the manager assumes the control of the application flow, leaving the activity as a dispatcher of input events.

These managers are part of the so-called, in the project terminology, a model; and the activity can be portrayed as the model manager. Conceptually a model is a set of software entities which live in the application and handle the data flow from a given data source towards a data holder, including or not, the visualization of such data. A model contains a Manager which is the entity responsible of the handling of the rest of the model entities. Please note that this model scheme is specific to the domain of the project and is not a general one.
This conceptual model scheme is provided by a subset of the classes and interfaces shown in Figure 3.1. For actual functionality building a realization of the model is to be developed, giving actual meaning to the scheme. In the scope of the project four model realizations have been implemented and will be detailed later.

A model realization is composed of implementations of the following elements from the core level exposed before: 1) a Manager, which handles user interaction and required preparations; 2) a DataSource that manages raw

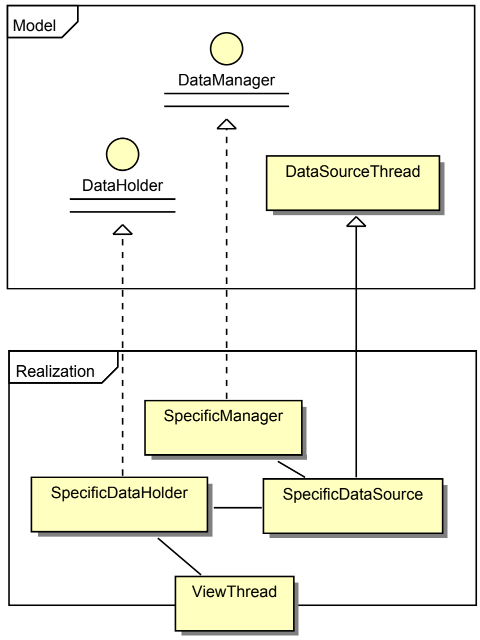


Figure 3.2: Data-flow model realization

data obtention from the actual source, and processing and sending of such data to a 3) DataHolder, which stores and handles the data in any required way and, if data visualization is required 4) an implementation of a view thread.

More detailed approaches to all the concepts exposed in this introduction are built throughout the following subsections.

3.6.1 View Package

The set of classes encompassed in the View package (see Figure 3.1) provides both a base rendering architecture in an update-render loop style not initially present in the Android framework and the specialization of such architecture for the specific project domain, i.e. plotting of the electrocardiogram wave and its relevant points.

Regarding rendering Android provides a set of common employed visual elements. These implementations try to simplify the developer's work by giving customizable solutions to common scenarios, such as rendering a list

of elements or a drop-down selection object, in a visually pleasing way. All these elements are part of the hierarchy of Android's View class, and implement a composite pattern for rich menu-building.
The soft real-time rendering imposed by the project restrictions requires an specific View [29] class derivate: the SurfaceView. This kind of View provides a bitmap surface where pixel-level rendering is allowed. A set of rendering tools is also provided by Android. The architecture developed on top of that view extends the SurfaceView to an AnimationView and delegates the rendering to an AnimationThread. This last entity is the one providing the update-render loop employed for the real-time rendering. The drawback of employing a SurfaceView as the base is that such element does not provide common employed functionality as scrolling or zooming.

The actual, domain specific rendering functionality providing threads are implemented employing the aforementioned layer as a base. The precise entities are DynamicViewThread and StaticViewThread, and are referred in this document as implementations of the view thread, even if such class does not exist in the project. This two classes implement the required behaviour for dynamic and static data visualization respectively, and obtain the data to be shown from a data source entity. Such entity is dealt with in the following section. The reason for different entities to exist for static and dynamic rendering is also detailed there.

3.6.2 Data Management Package

This package contains data storage and handling related entities. Differentiation between two types of data managed by the application depending on their purpose is mandatory. On one hand is the application level data, which is specific or non-specific information shared by the whole application. On the other hand is the data received from a source that must be visually presented to the user or stored for later visualization. Providing software tools allowing the modelling that data flow is the key task of this package.

The class Data acts as a centralized application level data storage. It is a singleton and is accesible by every entity in the system. It also provides synchronization methods for correct inter-thread communication.

The rest of the entities of the Data package are employed in the aforementioned model scheme, and specify the expected behaviour of each element involved in a data flow. As indicated before, specialization of these entities is required for the realization of the model.

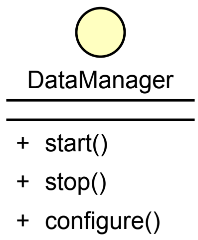


Figure 3.3: DataManager interface

DataManager is the interface to be implemented by the model controller. It is responsible for the configuring, starting and halting the data flow provided by its controlled entities. It also participates in the process of initialization of the visualization of a data flow by communicating a DataHolder with the respective DataSourceThread.

A DataSourceThread is a thread which provides data to other entities in the system, generally to a DataHolder. It is a specialization of Thread with functionality to start and stop the flow of data. This data is usually received from an external entity, such as a USB device or a file, and concrete implementations might require an actual communication between the two, forcing the DataSourceThread to send data to the other end of the connection. Because of that, any specialization of this class must also listen to petitions of writing to its data provider when available.

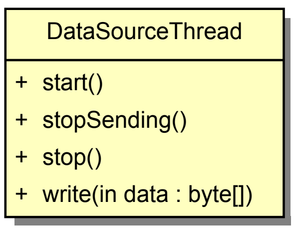


Figure 3.4: DataSourceThread class

The processing of raw data sent by the data providers to the DataSourceThreads is expected to be done in the latter, so the data transferred throughout the application is of a processed nature. To this end the DataParser entity from the Utilities package is available.

The expected receiver of the data sent by a DataSourceThread is a DataHolder. This interface provides domain-specific data handling abstract methods and definitions. An implementation of a DataHolder must handle the reception of ECG wave samples, delineation points, synchronization points and heart-beat-rate values.

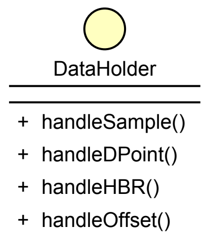


Figure 3.5: DataHolder interface

The actual way in which that data is employed depends on the concretion of the interface, and might or might not involve visual representation. When visual representation is required, the view thread implementation should also implement the DataHolder interface.

There are two different specifications for the data holders: DataHolder and StaticDataHolder. This is so because of the two modes of operation of the application. One is real-time data visualization and the other is log file visualization. The former is called dynamic visualization and the latter static visualization, and the behaviour of their DataHolders is not the same.

Dynamic visualization represents data received in real-time by the DataSourceThread. The DataSourceThread obtains the data from an external entity, processes it and sends it to the DataHolder. This data usually arrives in groups of variable size, and is provided to the DataHolder in single units once processed. In this scenario the DataHolder is the view thread, and handles data however considers optimal. In the implementations developed in this project a fixed amount of data is held and older information is replaced by the new one as it arrives.

Static visualization, on the other hand, involves reading a file, usually megabyte sized. The reception of big quantities of data in single units by the data holder, as would occur if the original DataSource specification was employed, could lead to severe slow-downs and application performance would be affected. To avoid such issues, the StaticDataHolder specification is developed.

A StaticDataHolder does not actually hold the data: it delegates that task to its DataSourceThread. The data source will provide the StaticDataHolder with a reference to the actual data. This way big amounts of data transferring is avoided. The inheritance relation between DataHolder and StaticDataHolder is imposed by the architecture, which requires a DataHolder to be passed to a DataSourceThread.

3.6.3 Utilities Package

This package contains reusable components providing very specific functionality so they are considered utilities: RealTimeDataParser, StaticDataParser and Viewport.

A data parser is the entity responsible of the processing of the raw data obtained by a DataSource into the domain specific data that the application manages. There are two implementations, one for real-time data reception, RealTimeDataParser, and the other for static data reading, i.e. a log file. The real-time data parser is also responsible of storing the received raw data to a log file.

A data parser is intended to be contained in a DataSourceThread. It receives the bytes of raw data and, upon successful identification of a valid data element, notifies the corresponding DataHolder entity of the arrival. In a theoric, performance-independant model, this behaviour would be incorrect: the data parser would leave the processed data *in* the DataSourceThread, which would then make the transfer of information to the data holder. This kind of implementation is not valid with the soft real-time requirements of the project, as the data source - data parser - data source - data holder flow would be a severe bottle-neck.

The Viewport entity is a container for the visualization area settings. It represents the window in which the data plotting is done, and holds information about size and position of it. It also contains data about the horizontal and vertical scale of the rendering and handles modification of all these parameters. It is employed by the view thread hierarchy.

3.6.4 Data Flow Model Realizations

Having explained the data flow model scheme and the core level architectural elements employed in its construction, model realizations implemented are detailed next. For each realization, the concretion of each model element will be exposed including particular details of such implementation.

Bluetooth Model

The Bluetooth model is a real-time visualization targeted data flow where the actual data provider is a Bluetooth node. As visualization is an objective, this model realization employs a DataManager, a DataSource, a DataHolder and a DynamicViewThread; the latter two being implemented in the same entity. An overview of the realization is shown in Figure 3.6.

The specialization of the DataManager is the BluetoothManager. It prompts the user for the device to connect to and handles connection by employing two threads: ConnectThread and ConnectedThread. After discovering the available nodes, it locates the node indicated by the user and launches the ConnectionThread.

This ConnectThread is the thread which actually manages the connection by obtaining its endpoints in the form of a socket. If successful, passes the socket to the manager and finishes its execution. The manager then launches the ConnectedThread, which receives the socket and data flow starts. The reason for employing a thread for establishing the connection is to avoid blocking the application while connecting.

ConnectedThread is the DataSourceThread implementation and contains an entity of DataParser. It receives data sent by the Bluetooth device through the socket, parses it and notifies the DataHolder implementation, which is the DynamicViewThread. The DataParser in DataSourceThread is a RealTimeDataParser and stores the data in a log file while processing.

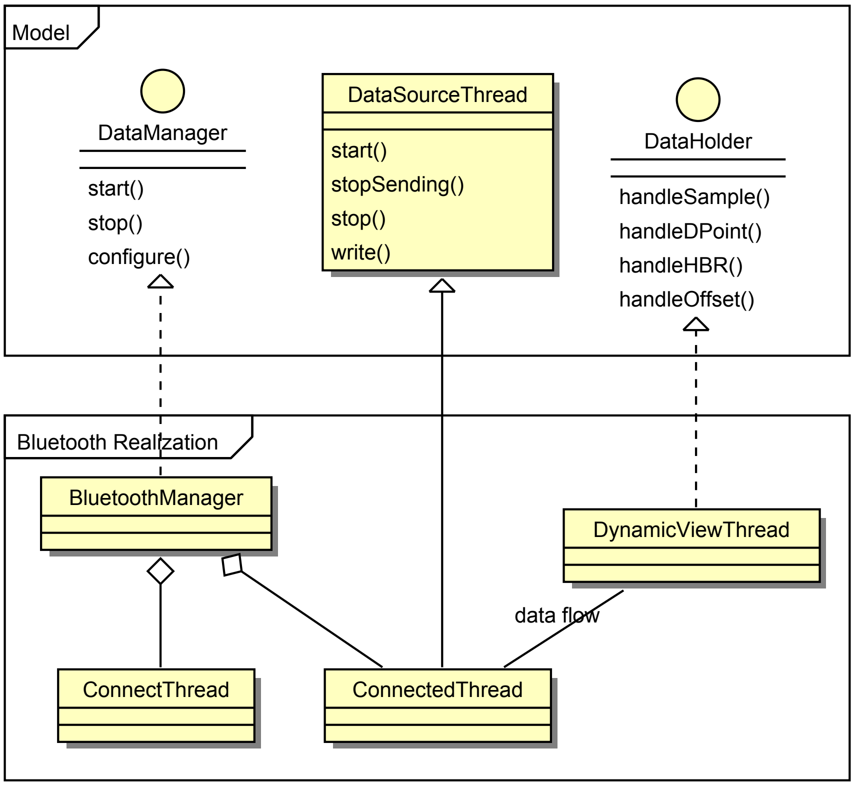


Figure 3.6: Bluetooth Model Realization

File Reader Model

This model realization implements visual representation of ECG data stored in a log file. It is a static view model, in which the user controls what section of the temporal log is shown on-screen, an thus employs an StaticViewThread instead of a dynamic one.

The manager in the file reader model is the FileManager class. It presents available log files to the user, handles the selection of one, instantiates the file reading thread and connects this with the view thread. When the user finalizes the visualization of the selected log, the FileManager returns to the log selection menu instead of going directly to the main menu. This is an example of the versatility of the aforementioned view stack scheme, which lets specific managers present as many menus to the user as necessary.

FileDataSourceThread is the thread that reads the chosen file and processes its data. It implements both the DataSource and the DataHolder interfaces,

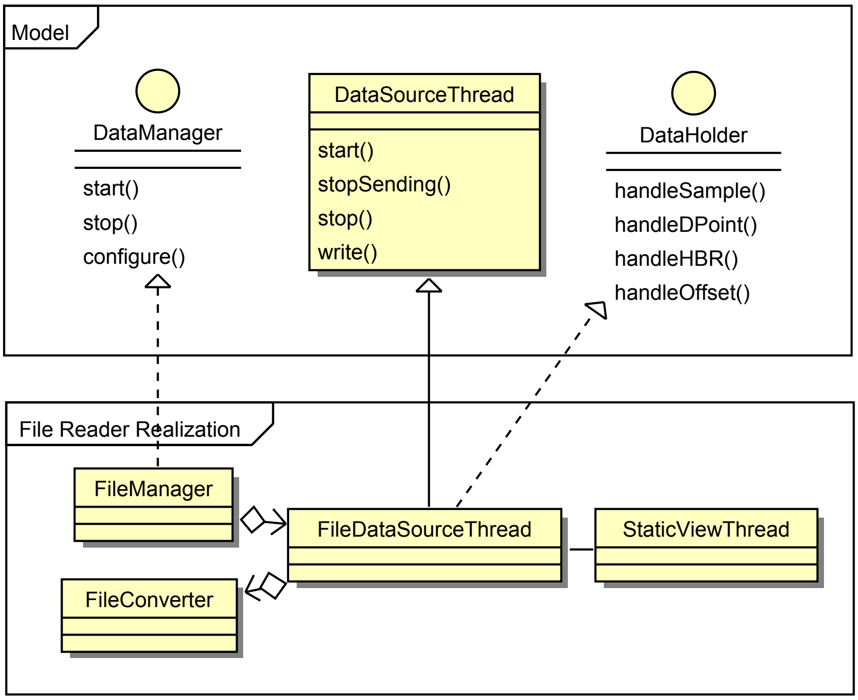


Figure 3.7: File Reader Model Realization

so it acts as the emitter and the receiver of the processed data. The view thread obtains a reference to this same data, thus avoiding big amounts of data transferring in the static view model as explained before. This is an example of the flexibility sought by the architecture design.

The FileDataSourceThread, thus, manages data reading, storage and manipulation. The data is read from files with the aid of the FileConverter entity from this package. This files can be of big size, so they should not be fully loaded onto memory. A partial load is mandatory in such cases, and the next chunk of data is to be read when the "visualization window" approaches. All this management is done by the FileDataSourceThread.

When the view is controlled by the user, i.e. horizontal scroll, the event is passed directly into this thread from the StaticViewThread. FileDataSourceThread then updates the portion of the data to be shown. The updated information is consulted by the view thread in the next rendering step. That way, were further file reading required, it could be done in a transparent-to-view manner.

Data processing is done employing an instance of StaticDataParser in the FileDataSourceThread.

The FileConverter entity provides functionality to transform a given file to an Stream, ArrayList or array of bytes, the latter being the expected input format for the available data parsers.

USB Model

The USB model manages data reception from an USB device and eventual visual representation for the user. It is a real-time data flow, and thus employs a dynamic view thread. An overview of the model is shown in Figure 3.8.

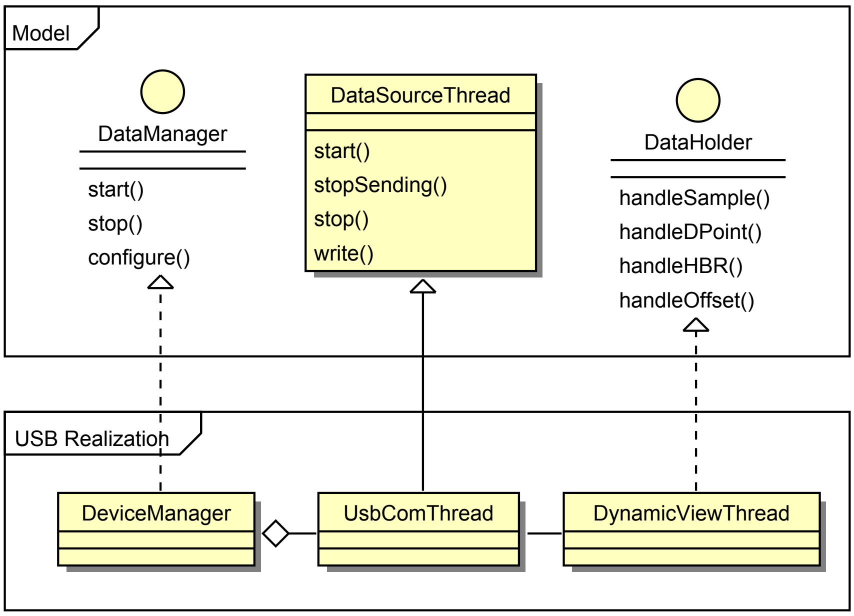


Figure 3.8: USB Model Realization

DeviceManager is the realization of the Manager of the model. This entity handles connected USB devices enumeration and selection by the user. If only one device is available, connection is directly stablished with it. Differing from the Bluetooth realization implementation, the actual connection to the device is handled by the DeviceManager in a blocking manner. It is so because USB connection resolution takes very little time and the delay is virtually imperceptible for the user.

Once the connection is stablished, the DeviceManager launches an instance of UsbComThread. This thread is the specialization of DataSourceThread and obtains the raw data from the USB device, processes it employing an instance of DynamicDataParser and sends the results to the view thread. This is a DynamicViewThread entity.

3.7 Development Process

In this section a detailed description of the development is presented. The evolution of the application architecture and functionality; design, architectural and implementation decisions and explanations of the circumstances in which they were made, as well as the development of the project schedule are exposed in chronological order.

The section is arranged following the five iterations of the project, developing each one by presenting the target objectives and expected deadlines for the iteration, detailing application evolution with emphasis on use case realization and risk suppressing achievements and demonstrating the state of the project as assessed on the reviewing meeting conducted at the end of the iteration.

3.7.1 Project Scheduling

Before diving into the description of the development process an overview of the project schedule is mandatory.

As it was mentioned in the previous sections, an agile software development methodology has been applied to the project, even if artifacts from more ordered and structured methodologies have been employed to avoid losing focus on the critical aspects of the development.

Software development project being dependent on parallel-conducted hardware research, project assets, both personal and development resources, being shared with the hardware research having the former higher priority, and the team's lack of formation regarding Android development are some of the factors which lead to the adoption of such a mixed methodology. As they have been already exposed in previous sections, they will not be detailed here.

In such an scenario, a fully developed, eight month covering schedule is unfeasible, at least with the imposed time restrictions which does not allow much time to be spent on planning. The decision is then made to plan only the earlier project iterations, assuring critical functionality identified from use case development to be implemented as soon as possible as well as higher threat involving risk suppression to be realized.

Actual software project development begins October 15, 2011, being the final deadline set on June 15, 2012. That deadline can not be pushed any further, so an estimated deadline is set on May 31, 2012, leaving half a month for further work or recovering from delays, and seven and a half months of development time.

Time is needed for the hardware research to start providing results, and no work can be done in the meantime on related application parts. Considering also that even in the most optimistic scenarios no actual work with the 802.15.4 USB receiver could be done until mid February, the schedule has to assume that the first four months of software development will need to cover the implementation of most of the features, leaving the rest of the development time for implementing hardware-related requirements, which could not actually be scheduled until hardware research was evaluated.

The adopted schedule deals with the aforementioned facts by proposing five iterations, from October 15 to May 30, complying with the fifteen days reserved for contingencies. The first three iterations have a duration of two months, the third one, of a single month, and the remaining one is fifteen days long.

Having the previously developed iOS application as starting point, and being achieved at least the same feature list of that a critical target of the project, the first two iterations are planned so as to realize **UC1** and **UC3** which capture requisites expressing such feature list.

The next iterations are just scrapped as no accurate estimation can be done on the state of the project by those dates. Thus, the third iteration is planned to cover the implementation of the remaining features, namely, communication with the 802.15.4 receiver device, the fourth one reserved for polishing the application and the fifth one left for testing and validation.

The fourth iteration is to shrink if objectives are achieved quickly to leave more time for validation.

The scheduled distribution of work for each iteration is as follows:

It	Dates	Activity
1	Oct 15 - Dec 15	Application base and Bluetooth module
2	Dec 15 - Feb 15	Log module and initial USB module
3	Feb 15 - Apr 15	Final USB implementation
4	Apr 15 - May 15	Polishing
5	May 15 - May 30	Validation
-	May 30 - Jun 15	Reserved

Which can be seen as the following expected use case realization dates:

It	Dates	Realized Use Case
1	Oct 15 - Dec 15	UC1, UC4 (first version)
2	Dec 15 - Feb 15	UC3, UC2 (first version)
3	Feb 15 - Apr 15	UC2 (final)
4	Apr 15 - May 15	UC4 (final)
5	May 15 - May 30	Validation
-	May 30 - Jun 15	Reserved

Throughout the development, as expected, this schedule has to be adapted as the hardware research advances to assess the arise of difficulties and subsequent changes to its planning. Instead of providing a fixed snapshot of the altered schedule at the end of the project, a detailed description of each iteration is presented next, including modifications to the planning and the motivation for making them.

3.7.2 Iteration 1

The main objectives for this first iteration are

- the instruction of the team on Android development,
- the lay out of an initial version of the application architecture and
- the implementation of the Bluetooth receiver module.

The alloted time for the iteration is of two monts, from October 15 to December 15. During this period the hardware research does not require much resources, so in practical terms the full team is employed in the software project.

In order to minimize risk AR1, the instruction of the team on Android development becomes the key objective for the iteration. Development starts with the implementation of the designed base architecture for the application, so it serves as a powerful learning resource. The notion of that implementation as disposable is not abandoned throughout iteration time and it is always considered as a prototype to evolve or be substituted by a more refined version once the team's knowledge of Android increases.

Having the basic architectural framework developed, implementation of the Bluetooth receiver module begins. Special care is put both on design and implementation, as this functionality has to be ready as soon as posible, and little time will be available for reimplementation further in the development.

Testing of both architecture and Bluetooth module is conducted during the whole iteration, specially in the final weeks, so by the end of the iteration Bluetooth module is validated and expected to be stable until the scheduled architectural redesign.

As the Android formation phase takes less time than expected and hardware research does not allow advancing into next iteration at the time iteration objectives are achieved, an extra implementation effort is put to begin implementation of UC4. Adjust View Parameters.

In the review meeting for the iteration the following conclusions are obtained:

- Basic architecture implementation is done.
- Android is confirmed to be a very comfortable development environment even if non-standard functionality is not that easily achieved. Instruction is planned to continue.
- Realization of UC1- *View data from Bluetooth* is finished. Related user interface is not final, but it is functional, and is to be updated on further iterations.

- Realization of UC4-*Adjust view parameters* is done in relation to Bluetooth visualization. As remaining modules are developed, further work is to be done in this field.

3.7.3 Iteration 2

The main objectives for the second iteration are

- the development of the USB communication module and
- the implementation of the Log visualization module.

The hardware reserarch having provided successful results regarding the initial prototypes of the USB accessory, the scheduled USB module implementation for this iteration is mantained, but delayed until further testing can be done in the hardware area. In that scenario this iteration begins with the implementation of the log visualization module.

Module design and implementation are to change little in following iterations to allow the scheduled architecture rewriting to be realized and trying to minimize the possibility of risk PR1. This situation and the fact that a lot of resources are required in the hardware area makes the achievement of this objective fill most part of the iteration time.

Full expected functionality is implemented, including the remaining features from UC4-Adjust view parameters, but validation testing indicates low performance in log visualization caused by big memory requirements. Effort needs to be put into the other iteration objective, so log visualization is halted at this point, scheduling the development of required optimizations for the next iteration.

Having the USB accessory prototype in an usable state, development of the USB communication module begins. At this point the USB accessory could only operate assuming the role of host in the connection, so the disposability of the module is acknowledged. Nevertheless, this implementation is a must if the project goals are to be achieved, as it serves as first-hand instruction regarding USB development in Android. Moreover, if the hardware project is unable to produce an USB slave accessory, with the developed module the project would not have fully failed. Eventually this development has proven being key for the first tests with the actual target hardware platform.

During the implementation of the USB communication module the log writing is improved, so, except for the aforementioned performance optimizations, the log part of the application is finished.

With the basic interface, disposable architecture and fully functional data flow modules, full application functionality is implemented by the end of the iteration, and in the review meeting the following conclusions are obtained:

- Full functionality has been implemented in the application and the product of this iteration is, as expected, the first prototype of the application.
- Realization of UC2-*View data from USB Receiver* is done until hardware research advances. Current implementation can act as the actual version of the use case realization if hardware research is not fulfilled.
- Realization of UC3-*View data from file log* is done.
- Realization of UC4-*Adjust view parameters* is now finished. All required view controls are implemented.
- Risk PR1-*Functionality of the application is inferior to that featured by existing iOS application* is marked as surpassed, as key functionality is implemented.
- Risk MR1-*Mobile device unsuitable for target functionality* is identified to require further monitorization and is unfolded into risks AR2 and AR3.
- Risk AR2-*Android providing subpar performance when handling required data* is confirmed to occur and is to be solved in the next iteration.

3.7.4 Iteration 3

This is the first just-drafted iteration of the original scheduling. Taking the prototype obtained in the previous iteration, architectural redesign and performance optimizations are mandatory. Performance optimizations are identified to be required in two areas: data management and data rendering. Only data management related optimizations are addressed in this iteration.

Iteration objectives are as follow:

- redesign of the application architecture,
- achievement of required performance on data management, and
- scheduling of the rest of the project time.

The main lack of the basic architecture of the protoype is that it was implemented to serve as a quick prototyping base for the data flow modules. The instruction and knowledge about the platform and the way of operation obtained in the previous iterations are applied in the new architecture design.

This design is done targeting easy inclusion of new data flow modules allowing them to employ their own user interfaces, while providing core level software entities for building those modules. This process produces the architecture as exposed in section 3.6.

A detailed analysis is conducted on the data management related operations in the application, identifying the ubiquitous application of the object oriented model proposed by Java added to the subpar efficiency of the Garbage Collector as the main cause of performance loss. The alteration of the programming paradigm and the employment of as basic software entities as possible, avoiding continuous object instantiation, e.g. substitute an object containing the four parameters of a wave delineation point, by a more basic structure, like the same four numbers stored independently, prove to be the most effective methods of avoiding low performance.

Following such lines of operation, performance regarding data management is utterly improved in spite of a less developer-friendly programming environment. During this process the data flow modules (Bluetooth, USB and Log Viewer) are also tweaked.

The positive results obtained both in the software and hardware areas allow a solid review of the project schedule. The decision is made to keep the division of the remaining project time in two iterations, leaving the last, fifteen days period for unforeseen difficulties. Of the two iterations, the first is to be devoted to implementation of the USB host communication as hardware project estimates completion of a first prototype halfway the iteration; and the second, and last, iteration is planned to be employed in final testing and validation of the application against hardware prototype.

The following conclusions are obtained from this iteration's reviewing meeting:

- The architecture of the application is finished and validated.
- User interface is yet to be final and is to be addressed at the following iteration.
- Identified solutions for performance issues are to be applied in the rendering area.
- Risk AR1-*Lack of instruction on Android development delays workflow* is marked as surpassed as the team feels comfortable enough with Android development.
- Risk AR3-*Android rendering capabilities unable to handle required data* probability is increased to Moderate and is to be addressed in the next iteration.
- Risk HR2-*802.15.4 receiver device unfeasibe* probability is reduced to Low as hardware research is providing positive results.

3.7.5 Iteration 4

This iteration is scheduled to be the last implementation iteration, and its objectives are:

- the implementation of USB host communication,
- the achievement of required performance in rendering and,
- the implementation of actual user interfaces.

The USB slave accessory prototype is produced on time by the hardware project, and implementation of the actual USB communication assuming the Android device the host role is done in very short time, leaving room for achievement of the rest of the iteration objectives and following validation.

Employment of the identified working solutions for performance issues in the rendering area does not provide the expected results, and further research is required. The bottle-neck in the rendering process is identified to be the context change required by the rendering tools provided by Android. Meticulous research on Android developer resources provides no other solution than minimizing the number of calls to the rendering methods each step.

Emphasis is put to the realization of this task, but to no avail.

The problem is the big amount of data required to be drawn each rendering step. A mechanism is developed to minimize the number of lines drawn by joining similar valued wave points, and the performance is improved, but not at the desired level. Nevertheless further work in this area is postponed as the achieved performance lies in the range required by the non-functional requirements of the project.

Implementation of the actual user interfaces to be employed in the application is addressed next. The design of these has been done throughout the last two iterations. The implementation process takes more time than expected as Android user interface framework is quite specific, and requires adequation to certain rules that have to be studied beforehand.

The remaining time of the iteration is devoted to testing and validation of the application, which has reached a near final state. Conclusions from the review meeting follow:

- The Android application is finished and pending validation with the actual USB receiver device.
- The realization of UC2-*View data from USB Receiver* is done.
- The user interface of the application is in a final state, but were changes required they could be easily implemented as the UI is isolated from the data flow part.
- Performance regarding rendering is not optimal, but it is in the range defined by the requirements.
- Until validation can begin, the full team can be employed in the hardware project.
- Risk HR2-*802.15.4 receiver device unfeasible* is marked as surpassed as the viability of the receiver has been proved by the hardware research.

3.7.6 Final Validation

The final effort in this software project extends over the allotted time for both the fifth iteration and the reserved final period. It is fully devoted to testing and validation of both the application and the receiver device. Even

if the initial schedule assigned only the fifth iteration to this process, delays on the hardware project force the elongation of the testing phase.
The objectives for this period are:

- exhaustive testing of the Android application,
- validation of the application, the receiver and the delineator node acting as a whole, and
- the obtention of the final version of the system by implementing the required amendments identified by the testing procedure.

Software related testing is conducted throughout all this final step causing minor fixes to be done to the application. No relevant software related issues arise during the testing or the validation phases.

Risk HR1-*802.15.4 receiver device delayed* occurrence is the cause of the elongation of the validation iteration, but has no actual effect on the software project. Even when the receiver is completed the risk tracking is continued until validation concludes, were hardware complications to arise during the process.

The final, review meeting conclusions are as follow:

- Risk HR1 is marked as surpassed.
- The Android application is successfully validated and, thus, completed.

3.8 Closure

The software development part of the project has been able to produce the required Android application, with all planned functionality implemented and including user friendly interfaces. It is a rather general purpose application inside of the domain to which it is restricted, and at its final state it would need some specialization in order to be actually useful. This is so because the requirement analysis process was not developed focusing on an immediate professional employment of the application, but a replacement for that of the UCM and EPFL project which inspired this one.

Anyhow, during the architecture design and subsequent implementation phases great emphasis is put for the application to provide the tools to act as a framework over which more specific ECG monitoring application development can be realized. An interesting example of this is that, at the current state, the application implements visualization of data received from an USB device. In this project, the USB device has been the 802.15.4 USB receiver, but any other device capable of encoding the data in the expected way is valid as well.

In short, the software development finished providing successful results in form of a general purpose ECG monitoring application for Android devices which can serve as the base for more specific developments, which was exactly the target objective for the software project.

Chapter 4

Results

4.1 Final state

The production of the fully functional, low energy requiring, low sized ECG monitoring system employing an Android device as the user interface and 802.15.4 as the wireless data transferring protocol has been achieved. The system provides all the required functionality: real-time ECG wave data visualization both from 802.15.4 and Bluetooth nodes and storing of the received data in log files for afterwards visualization of these, as well as visualization parameters configuration. The system is, then, a more energy efficient and accessible version of the one produced by the Complutense University of Madrid and the École Polytechnique Fédérale de Lausanne, which is the primary objective of the project.

This achievement is made thanks to the successful outcome of both the hardware research and the software development processes in which the project has been divided. Each of them requiring the employment of specific methodologies and techniques, but being, as they were, highly dependent one on the other only complicated the prediction of the outcome of them both. Thanks to the flexible scheduling conducted for each one, which considered the potential eventualities to arise in the other and focused in allowing rescheduling when necessary, this uncertainty has been correctly managed, leading to the current, successfully finalized state of the project.

Regarding the hardware research part, the main goal pursued was the production of the 802.15.4 USB receiver device for Android systems. This device has successfully evolved from the early stages of development where a prototyping board was employed to a custom developed printed circuit board which is completely designed, validated and is being produced at the moment of writing this document.

The dimensions of this board are 61 x 32 x 35 mm, and it requires 3.3V for correct operation, being usable with at least 3.0V. Its USB capability allows for it to be connected to any HID compliant system, and has been successfully employed as an 802.15.4 receiver both in Android devices and Windows based personal computers.

In respect of the Android application, the software development project has produced an Android application providing all required functionality, namely visualization of ECG data from Bluetooth and USB nodes, log saving and reading, and view controlling capabilities, designed and implemented in a robust, expandable manner. Moreover, the application provides a domain-specific framework for the inclusion of new data sources (like Wi-Fi or Near Field Connection) or different source data specifications.

The application presents simple, easy to use user interfaces and very specific functionality, which added to the following of Android proposed application design best-practices smooth the learning curve and allow out of the box usage of the software part of the system. Due to the expansion capabilities of the system, new user interfaces or dialogs can also be added with ease.

The webpage for the project is available at:

`http://jrecas-ws.dacya.ucm.es/doku.php?id=projects:ecg_android`

Besides this document, the webpage contains both the source code of the Android application and the schematic files of the receiver device, as well as further info on the project.

4.2 Potential additions and expansions

Although every initially planned objective has been fulfilled, in addition to several of them which were added during the development, there is still room for improvements and features which were not considered or left out of scope, since the developed application is not considered as a specific product itself, but a framework for further developments. These improvements can be classified according to the period planned for their implementation:

- **Short-term:** the following features specifically target personal use. Considering the user is to monitor his/her own vital signs, the next additions are thought to be useful:

  - *Event Tagging*
    Assuming the user is feeling funny or pain, it may be quite interesting for him/her to be able to annotate such an event with later revision purposes, either by him/herself or medical staff. Furthermore, the capability of marking down one peculiar result about the ECG delineation can also be useful.

    In this way, making use of the tactile interface the Android tablet features, this activity can be done by simply touching the relevant event or result. Next, the moment which that points refers is logged and a comment may be added to the annotation.

  - *Temporal Meta-Data*
    In the same conditions described in the previous item, it is possible that the user had felt a particular sensation in a certain moment, yet he/she was unable to mark it. Moreover, maybe the annotation was done and it is required to directly jump to that certain time.

    In order to ease these tasks, time-related data is to be added so that a precise moment of the monitoring can be directly found. In this way, the user can input the desired date so that the application shows what was happening at that moment. In addition, markers from previous annotations would also appear for quickly accessing to relevant events.

  - *Voice Commands*
    Due to the particular health condition of the user, or just because he/she is busy, direct interaction with the monitoring Android device is likely to be impossible. If situations like these are to happen, letting users interact with the system through their own voice may ease the aforementioned tasks.

Fortunately, Android provides speech recognition support throughout its specific API, so this feature could be added without developing the whole voice recognition framework.

- *Automatic Warnings*
  Regarding the user's health condition or unavailability again, automatic message sending with ECG data in case of relevant happenings were detected would mean a seamless way to warn the user, relatives or qualified staff if needed. In the same direction, multiple alternatives would be presented such as emails with GPS location attachments or direct automatic voice calls to complement this feature.

All these features come from a potential project proposed by an specific individual, which, being affected of a certain cardiovascular disease and considering the goals and results of this specific project, has shown interest in further specialization of the developed system for his particular needs. This private enterprise is yet to be started, but the inception phase has already begun, and is seeking funding. The team of the current project is offering consulting on the viability of the requirements of the project, and testing has been conducted of the already available system with the interested individual.

- **Long-term:** this features are mainly ideas which would grant the system with much richer capabilities and new potential, though it would require of a greater amount of time along with specific planning and dedication.

  On one hand, the application can be focused towards professional multipatient monitoring, which could be developed in at least two alternative ways:

  - Since the developed 802.15.4 USB receiver is also compatible with HID-compliant devices, particularly computers, multipatient monitoring could be uploaded to a devoted server from a variable number of wireless delineaton nodes, omitting the displaying service the Android application provides. Once the data is uploaded, the Android device could connect with the mentioned server and download the information right from the developed application. Then, the Android tablet would act as usual as frontend of the monitoring process, displaying the downloaded data.

– Taking into account the relatively big display a tablet device provides, this multipatient monitoring paradigm could be directly implemented into the Android device by extending the application's functionality. Among this new functionalities there would be switching between ECG wave visualizations of different patients, simultaneous logging and server uploading as well.

On the other hand, regarding self-monitoring, the system can be adapted to be applied to specific domains which impose additional time or resource restrictions. Specifically the director of the Embedded Systems Laboratory at the EPFL, where the delineator node employed in this project was produced in the aforementioned collaboration with the UCM, has shown interest in the application of the low power requirements of the system in a specific project the EPFL is collaborating with: Solar Impulse [30].

This particular project tries to achieve a flight around the world employing no fuel, just the energy collected from the sun. The airplane used in the project allows only for the pilot to be in the cockpit throughout the flight, and, thus, he/she is required to be constantly monitorized. Among others, ECG monitorization is required, and is, at the time, being provided by the EPFL and UCM monitoring project with the already exposed battery implications of the employment of Bluetooth as the wireless technology.

Considering that the space in the cockpit is very reduced, and the amount of wires, sensors and other instruments that are present, any operation is to be done with special care and only when absolutely needed. Concretely, the swapping of a battery-exhausted delineator node for another, fully-charged one, to allow the recharging of the first, is a complex procedure as the body sensor network wires have to be unplugged from one node and plugged into the other. Moreover, while this procedure is being performed ECG monitorization is interrupted.

> Reducing the battery consumption of the delineator node is then, a must, and can be achieved by the employment of 802.15.4 as the wireless communication protocol. Because of that, the results obtained in this project can be of great use to the Solar Impulse project.

4.3 Findings

At this point, with the development finished and having analyzed the project results and further work lines, it seems relevant to point out some of the findings drawn from the development of the project as a conclusion for this document. They have been obtained both during the development process and from the results of it, near the ending of the project.

At the inception phase of the project, even having already decided to employ Android systems as the real-time data display for the system, the team had doubts about the actual applicability of Android as a base for the development of real-time applications like the one to be built in the project. During the development the fact that Android may not be the fittest environment for this kind of functionality became clear, as, even if the devices have, in general, high computational power and graphic capabilites, the restrictions imposed by the operating system substantially complicate the development of reliable real-time functionality.

In a system like the one developed in this project, the application of an specific display device would allow finer, prettier even, visualization of the ECG data within the real-time restrictions in which it needs to operate, but the benefits of employing Android significantly compensate for the aforementioned lacks. The most important of this benefits, at least in the scope of the project, are the simplicity of development of visually rich applications Android provides and, more importantly, the high availability of Android supporting devices. These have been exposed throughout this whole document, but they seemed worthy of one last remark. The selection of Android as the application target platform, assuming some limitations to the application, which already can, or eventually will be able to, be overcame, has been one of the best decisions made in the project.

Even with the simplicity of development provided by the Android development kit, a development process, such as the one conducted for this project, that spawns various subprojects with different characteristics and each dependent on the overtaking of specific achievements on the other can be an specially complicated task to overcome if braved incorrectly. Moreover, the inherent uncertainty of the hardware research required even more care to be put in the scheduling tasks.

Through the project development some key techniques have been applied and have proven to be of great relevance for the successful outcome of it. These are, as exposed before, the employment of a flexible schedule to allow change-prone, supposition based planning; a detailed risk management procedure to be prepared for countering the difficulties arised from planning modifications; and mantaining a constant focus on the current objective, as well as its deadline and dependant tasks, thanks to a use case driven development process. Great part of the success on the achievement of the objectives of this project can be granted to the careful application of these techniques.

Assessing now the utility of the performed development, the importance of monitorization systems for specific cardiovascular diseases affected people has become a reckoned fact through the development process. There is great potential of development in this area, specially when considering that these systems are bound to be used as a daily basis by people who need them. Projects targeting this field of interest must always consider the final user throughout the whole development as a little user oriented extra effort, like reducing the operations needed for monitorization initialization or simplifying the way in which the user inputs his/her commands, as small as the improvement may seem to be, can substantially improve the quality of life of the user. This is so because when using a system day after day, apparently minor nuisances in the system interface can become a constant source of frustration.

Production of a low energy requiring monitoring system contributes to this by reducing the amount of interruptions to the monitoring process due to battery recharging procedures (and the subsequent halt of common activity because of these). As mentioned, thanks to the employment of the 802.15.4 wireless protocol, the life of the battery on the delineator node is improved in two orders of magnitude, which means recharging it once a week instead of twice a day.

On the same line, employment of Android instead of iOS allows the monitoring application, which displays, and more importantly, logs the ECG data, to work in background in such a way that the operation is not interrupted by common events such an incoming phone call or the need to look something up on the Internet. Another important feature provided by Android is the ability for the applications to continue running when the device enters low power modes by, for example, disabling the display. Again, these may seem like small features, but for a person who needs constant monitoring they are of great importance as they affect his/her day to day life activity.

As if to corroborate these claims, when the project was entering the final phases of development, before even the beginning of the validation procedures, a cardiovascular disease affected person contacted the department to which the project is bound and shown great interest in this particular endeavour after being informed of the project goals and already achieved results. Further interaction with this person produced the potential short-term project explained in the previous section for the specialization of the system for the particular needs of the specific cardiovascular disease. This person is also in the process of testing the system in an actual employment scenario such as him/hers, the feedback from this yet to come as the time of the writing of this document, and is willing to colaborate in as much ways as possible with the project, as it could be of great use for him/her.

Moreover, as exposed before, the director of the Embedded Systems Laboratory of the EPFL is also interested in the results obtained in this project for the application of them to the Solar Impulse project with the objective of constantly monitoring the pilot of the solar airplane. This airplane is equipped with a tablet device for various purposes, and the utilization of it as the monitoring display, as well as the reduction of the battery consumption of the delineator node as much as possible, being energy saving critical for solar flight, make this scenario a great one for the employment of the project results.

Needless to say, these signs of interest in the project make this endeavour a personal success regardless of its actual outcome. The fact that the work carried out throughout the last months is being confirmed to be able to provide actual benefits to some people, which was, at heart, the ultimate goal for the project, renders all hardship involved in the process as mere anecdotic when compared to the personal pride it has, at the end, provided.

Appendices

Appendix A

Budget Analysis

Throughout this appendix the project budget analysis is conducted, by detailed specification of both time and resource cost.

The project division in atomic tasks and the scheduling of these is exposed in the first section, in order to justify the cost in engineer hours. The tasks have been given sufficiently explicit names, and have been divided regarding the development iteration they belong to. The Gantt chart ilustrating the project schedule is presented next. Both the hardware and the software subprojects are presented together in it in order to achieve a finer understanding of the project progression.

Once the project scheduling has been exposed, the next section presents the asset cost analysis for the project.

A.1 Project tasks and scheduling

A.1.1 Hardware project tasks

T1.1.1	Acquire a suitable Android device prototyping environment	15/10/2011	16/11/2011
T1.1.2	Manage correct communication between Android and a prototype device	17/11/2011	11/12/2011
T1.1.3	Develop an application emulating desired behaviour	12/12/2011	19/12/2011
H1	Arduino for Android USB device Communication	-	19/12/2011

T1.2.1	Supply MSP430 with USB protocol application functionality	20/12/2011	04/01/2012
T1.2.2	Research Android USB protocol related functionality	05/01/2012	19/02/2012
T1.2.3	Make Android OS recognize MSP430 when plugged	20/02/2012	22/02/2012
T1.2.4	Manage communication between Android and MSP430 via USB	23/02/2012	07/03/2012
H2	MSP430 for Android USB Host Comunication	-	08/03/2012

T1.3.1	Check the proper working of FreeRTOS with the new microcontroller	09/03/2012	13/03/2012
T1.3.2	Validate the feasibility of the usage of USB API along with FreeRTOS in MSP430	14/03/2012	23/03/2012
T1.3.3	Correctly integrate USB API into FreeRTOS	-	31/03/2012
T1.3.4	Manage USB data sending in FreeRTOS	31/03/2012	02/04/2012
H3	USB in FreeRTOS	-	02/04/2012

T1.4.1	Validate current implementation of 802.15.4 in FreeRTOS in MSP430 testing board	03/04/2012	18/04/2012
T1.4.2	Manage connection to the CC2420 radio module to target MSP430 device	19/04/2012	21/04/2012
T1.4.3	Port implementation of 802.15.4 to target MSP430 device	22/04/2012	28/04/2012
T1.4.4	Prepare implementation of 802.15.4 for actual usage	28/04/2012	09/05/2012
H4	802.15.4 in FreeRTOS	-	09/05/2012

T1.5.1	Assess conflict-free coexistence of current implementation of both USB and 802.15.4 modules in MSP430	10/05/2012	16/05/2012
T1.5.2	Manage sending data received from 802.15.4 via USB	17/05/2012	25/05/2012
H5	802.15.4 & USB coexistence under FreeRTOS	-	25/05/2012

T1.6.1	Exhaustive analysis of the reference board	10/05/2012	21/05/2012
T1.6.2	Capture of the board schematic	21/05/2012	14/06/2012
T1.6.3	Design and routing of the actual PCB	15/06/2012	21/06/2012
H6	MSP430 based device design	-	21/06/2012

T1.7.1	Validate the final version of the receiver device	26/05/2012	16/06/2012
T1.7.2	Fix possible errors	N/A	N/A
H7	Final Validation and Release Candidate Version Development	-	16/06/2012

A.1.2 Software project tasks

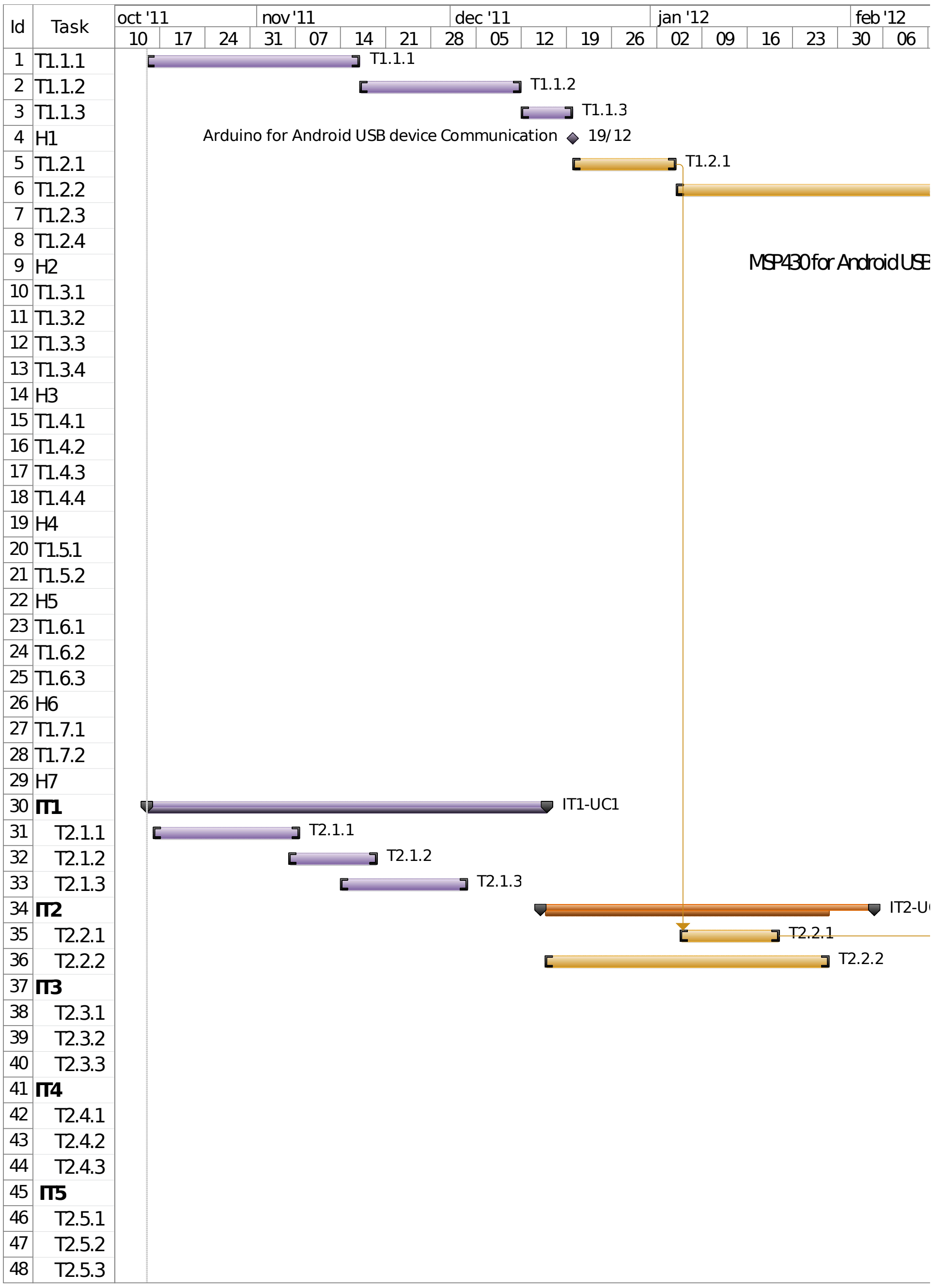
IT1	Complete UC1	15/10/2011	15/12/2011
T2.1.1	Instruction of the team on Android development	16/10/2011	07/11/2011
T2.1.2	Lay out of an initial version of the application architecture	06/11/2011	19/11/2011
T2.1.3	Implementation of the Bluetooth receiver module	14/11/2011	03/12/2011

IT2	Complete UC4, UC3	15/12/2011	04/02/2012
T2.2.1	Development of the USB communication module	05/01/2012	20/01/2012
T2.2.2	Implementation of the Log visualization module	15/12/2011	28/01/2012

IT3	Complete Redesign	15/02/2012	15/04/2012
T2.3.1	Redesign of the application architecture	16/02/2012	12/03/2012
T2.3.2	Achievement of required performance on data management	13/03/2012	28/03/2012
T2.3.3	Scheduling of the rest of the project time	28/03/2012	05/04/2012

IT4	Complete UC2	12/04/2012	11/05/2012
T2.4.1	Implementation of USB host communication	16/04/2012	26/04/2012
T2.4.2	Achievement of required performance in rendering	22/04/2012	07/05/2012
T2.4.3	Implementation of actual user interfaces	28/04/2012	11/05/2012

IT5	Final Validation	15/05/2012	22/06/2012
T2.5.1	Exhaustive testing of the Android application	15/05/2012	22/06/2012
T2.5.2	Validation of the application, the receiver and the delineator node acting as a whole	26/05/2012	22/06/2012
T2.5.3	Obtention of the final version of the system by implementing the required amendments identified by the testing procedure.	21/05/2012	17/06/2012



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1 T1.1.1
2 T1.1.2
3 T1.1.3
4 H1
5 T1.2.1
6 T1.2.2
7 T1.2.3
8 T1.2.4
9 H2
10 T1.3.1
11 T1.3.2
12 T1.3.3
13 T1.3.4
14 H3
15 T1.4.1
16 T1.4.2
17 T1.4.3
18 T1.4.4
19 H4
20 T1.5.1
21 T1.5.2
22 H5
23 T1.6.1
24 T1.6.2
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26 H6
27 T1.7.1
28 T1.7.2
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41 IT4
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43 T2.4.2
44 T2.4.3
45 IT5
46 T2.5.1
47 T2.5.2
48 T2.5.3
T1.1.1
T1.1.2
T1.1.3
Arduino for Android USB device Communication
19/12
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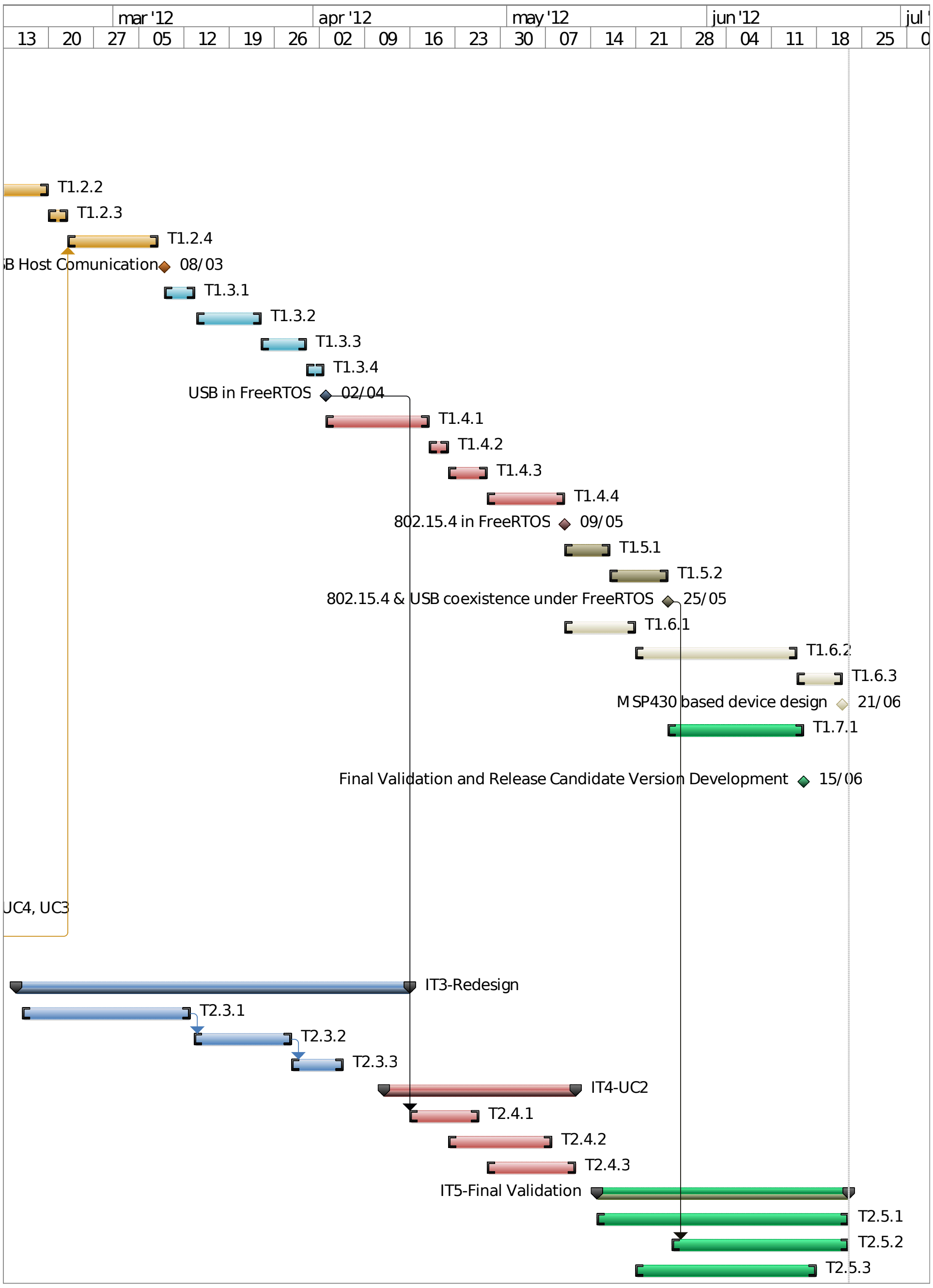

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T1.3.1
T1.3.2
T1.3.3
T1.3.4
USB in FreeRTOS 02/04
T1.4.1
T1.4.2
T1.4.3
T1.4.4
802.15.4 in FreeRTOS 09/05
T1.5.1
T1.5.2
802.15.4 & USB coexistence under FreeRTOS 25/05
T1.6.1
T1.6.2
T1.6.3
MSP430 based device design 21/06
T1.7.1
Final Validation and Release Candidate Version Development 15/06
UC4, UC3
IT3-Redesign
T2.3.1
T2.3.2
T2.3.3
IT4-UC2
T2.4.1
T2.4.2
T2.4.3
IT5-Final Validation
T2.5.1
T2.5.2
T2.5.3

A.2 Asset cost

The total asset cost of the project is presented next, considering the following assumptions:

- The project has been developed through seven months after deducting two months of recess.
- Three engineers have been employed halftime through the whole project.
- A halftime workday is considered to be of four hours.
- The engineer per hour cost considered is 35€ per hour.
- The ECG delineator node technology is donated and thus is not reflected in the price.

The cost of a single engineer employed halftime throughout the seven months is of 35€/hour $\times$ 4 hours/day $\times$ 22 days/month $\times$ 7 months = 21560€.

The breakdown of the cost of the assets of the project is now exposed.

Name	**Number**	**Price per unit**	**Total (€)**
Motorola Xoom - Wifi	1	399	399
Google ADK	1	70.80	70.80
Exp430F5438 + MSP430F5438A	1	117.89	117.89
TS430PZ100USB + 2xMSP430F6638	1	60	60
CC2420	1	4	4
Prototype	1	38.60	38.60
Final product	1	63.229	63.229
Engineer	3	21560	64680
Total			65413.13

The total cost of the development of the project rises to 65413.13€.

Appendix B

Product Cost

The cost of the production of both a single unit of the final board and an estimated mass production in batches of 10000 (ten thousand) units is as follows.

In this project a single unit of the board has been produced, with the following, exact cost (all quantities are expressed in Euro).

Name	**Reference**	**Number**	**Price per unit**	**Total price**
SMT	1022311	2	1.96	3.92
Resistor	1738981	2	0.062	0.124
LED	1699413	1	0.28	0.28
Capacitor	1833863	6	0.03	0.18
Capacitor	1740650	2	0.154	0.308
Capacitor	499110	2	0.114	0.228
Resistor	1469918	1	0.038	0.038
Capacitor	1833865	2	0.144	0.288
Diode	1469389	3	0.099	0.297
Capacitor	1833803	1	0.085	0.085
Capacitor	1327699	1	0.36	0.36
Resistor	1500615	4	0.028	0.112
Capacitor	644183	1	0.27	0.27

Name	**Reference**	**Number**	**Price per unit**	**Total price**
Capacitor	1740632	1	0.062	0.062
MSP430F6638	2070274	1	18.49	18.49
Capacitor	1833888	1	0.163	0.163
Capacitor	499160	2	0.122	0.244
ESD protection	1269406	1	0.63	0.63
Microcrystal	1539364	1	2.19	2.19
Capacitor	1658880	2	1.98	3.96
Radio	From TI	1	4.00	4.00
Manufacturing		1	27.00	27.00
Total				63.229

The resulting cost of the device is of 63.229€.

In a mass production scenario the cost of the individual unit is reduced, and an estimation of this is now presented.

Name	**Reference**	**Number**	**Price per unit**	**Total price**
SMT	1022311	20000	1.65	33000
Resistor	1738981	20000	0.017	340
LED	1699413	10000	0.156	1560
Capacitor	1833863	60000	0.005	300
Capacitor	1740650	20000	0.032	640
Capacitor	499110	20000	0.024	240
Resistor	1469918	10000	0.01	100
Capacitor	1833865	20000	0.024	480
Diode	1469389	30000	0.053	1590
Capacitor	1833803	10000	0.025	250
Capacitor	1327699	10000	0.063	630
Resistor	1500615	40000	0.021	840
Capacitor	644183	10000	0.159	1590

Name	Reference	Number	Price per unit	Total price
Capacitor	1740632	10000	0.012	120
MSP430F6638	2070274	10000	13.07	130700
Capacitor	1833888	10000	0.026	260
Capacitor	499160	20000	0.041	820
ESD protection	1269406	10000	0.42	4200
Microcrystal	1539364	10000	1.40	14000
Capacitor	1658880	20000	1.03	20600
Radio	From TI	10000	4.00	40000
Base mask		1	150	150
Manufacturing		10000	0.30	3000
Total				255360
Total per unit				25.536

Hence, the cost of the device produced in batches of 10000 (ten thousand) units is reduced to 25.536€.

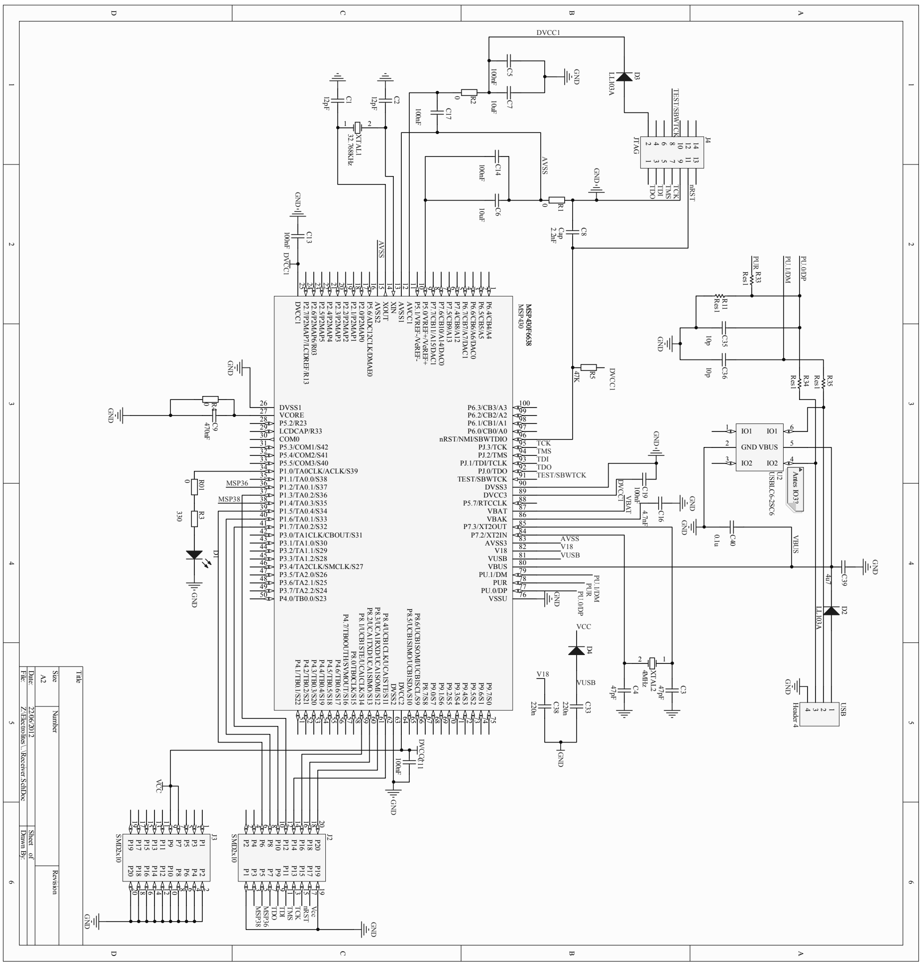
Appendix C

Receiver Specification Documents

C.1 Bill Of Materials

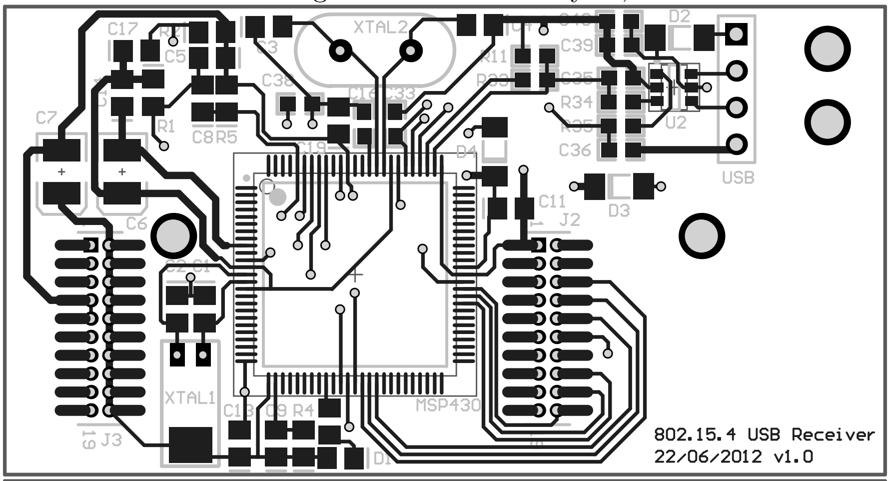
Comment	Description	Designator	Footprint	LibRef	Qty.
12pF	Capacitor	C1, C2	CC2012-0805	Cap	2
47pF	Capacitor	C3, C4	CC2012-0805	Cap	2
100nF	Capacitor	C5, C11, C13, C14, C17, C19	CC2012-0805	Cap	6
10uF	Capacitor	C6, C7	3.5x2.8x1.9	Cap	2
2,2nF	Capacitor	C8	CC2012-0805	Cap	1
470nF	Capacitor	C9	CC2012-0805	Cap	1
4.7nF	Capacitor	C16	0603	Cap	1
220nF	Capacitor	C33, C38	0603	Cap	2
10pF	Capacitor	C35, C36	0603	Cap	2
4,7uF	Capacitor	C39	0603	Cap	1
0.1uF	Capacitor	C40	0603	Cap	1
-	Green LED	D1	CC2012-0805	LED2	1
-	Default Diode	D2, D3, D4	MELF-D3516-1406	LL103A	3
2x10 pin	Header, 20-pin	J2, J3	MHDR2X10	SMD2x10	2
F6638	Microcontroller	MSP430	PZ100_L	MSP430F6638	1
0	Resistor	R1, R2, R4	CC2012-0805	Res2	3
47KΩ	Resistor	R5	CC2012-0805	Res2	1
1MΩ	Resistor	R11	0603	Res1	4
27Ω	Resistor	R34, R35	0603	Res1	4
1.4KΩ	Resistor	R34, R35	0603	Res1	4
-	ESD protection	U2	SOT23-6_L	USBLC6-2SC6	1
4 pin	Header	USB	HDR1X4	Header 4	1
32,768KHz	Crystal	XTAL1	XTAL MS1V-T1K	XTAL MS1V-T1K	1
4,000Mhz	Crystal	XTAL2	HC49/4H	XTAL MS1V-T1K	1

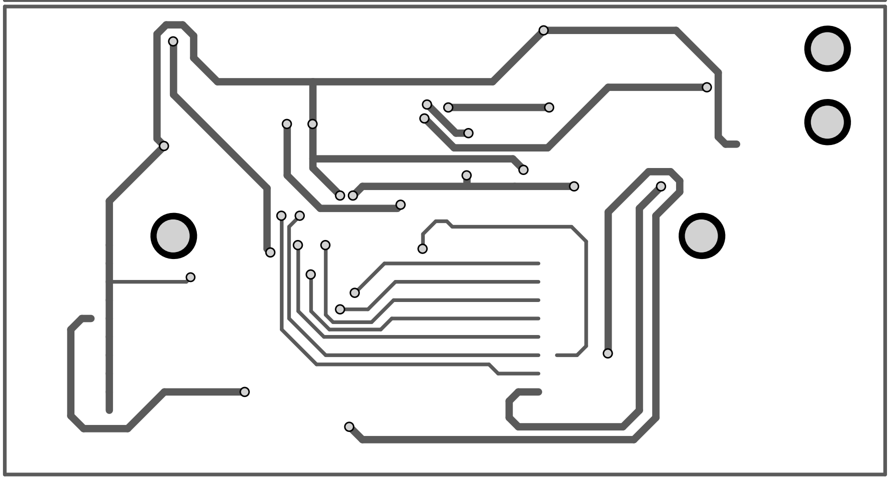
C.2 Schematic



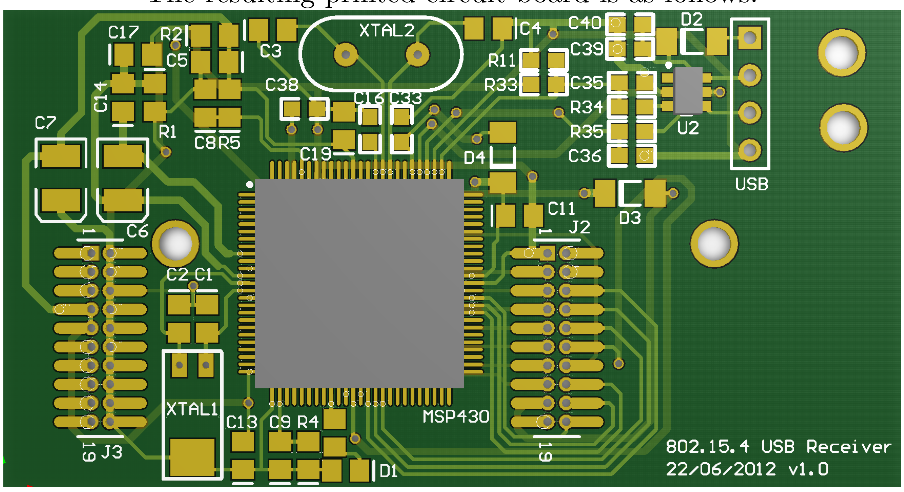
C.3 Printed Circuit Board Design

The board design is made in two layers, as follows.





The resulting printed circuit board is as follows.



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