News algorithms for green wired and wireless communications

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Résumé

La recrudescence et le déploiement de nouveaux services et applications dans les systèmes de communication, ainsi que le nombre toujours croissant d'utilisateurs, conduisent à une augmentation de la consommation d'énergie des réseaux et technologies de l'information et de la communication, ce qui contribue de façon significative au réchauffement climatique. Ainsi, pour satisfaire aux exigences énergétiques aussi bien pour les réseaux sans fil que filaires, de nouvelles approches doivent être développées.

Dans un premier temps, nos travaux de recherche se focalisent sur les mécanismes d'allocation des ressources de systèmes point-à-point dans deux modes de transmission (mono-porteuse et multi-porteuses) avec pour objectif la minimisation de l'énergie consommée. Dans cette partie, nous présentons une nouvelle approche appelée ultra large temps (ULT) ainsi qu'une nouvelle métrique pour les systèmes de communication. En se basant sur cette nouvelle approche, des algorithmes d'allocation des ressources sont proposés afin d'améliorer l'efficacité énergétique des réseaux sans fil et des réseaux filaires, dont notamment les réseaux CPL (courant porteur en ligne).

Dans un second temps, nous étudions les techniques impulsionnelles ultra large bande (ULB). Un simulateur logiciel de liaison point-à-point ULB impulsionnelle, générique et paramétrable a été développé. L'objectif est d'améliorer l'efficacité énergétique d'une liaison ULB. Les différents paramètres du système (largeur de l'impulsion, temps de garde, nombre d'impulsions transmises) sont exploités afin d'optimiser les performances du système. Ainsi, la forme d'onde ULB impulsionnelle a été dimensionnée afin de s'adapter au mieux aux caractéristiques du canal de transmission. Les résultats de ces travaux permettent de poser les premières règles d'ingénierie en termes de dimensionnement des systèmes de communication ULB impulsionnelle dans le cadre de la radio verte.

Enfin, la dernière partie de nos travaux se focalise sur la conception de l'impulsion dans les systèmes de communication ULB. Le choix de la forme de l'impulsion est très important pour améliorer les performances du système et pour économiser l'énergie. L'objectif est de trouver la meilleure impulsion pour minimiser l'énergie consommée tout en garantissant le niveau attendu de performances.

Abstract

The demand for new services and applications in communication systems, as well as the number of users, are steadily increasing. This growth involves a great use of energy in information and communications technologies, which contributes significantly to global warming. Furthermore, to satisfy the energy requirements for both wired and wireless networks, new approaches must be developed.

Firstly, our researches focus on resource allocation mechanisms in point-to-point systems for two transmission modes (single-carrier and multi-carrier) with the goal of minimizing the energy consumption. In this part, we present a new approach called ultra wide time (UWT) and a new metric for communication systems. Based on this approach, efficient algorithms for resource allocation are proposed to improve energy efficiency in wireless and wired networks.

Secondly, we study ultra wideband (UWB) communications. A software simulator of impulse UWB communications generic and configurable has been developed. The objective is to improve the energy efficiency of UWB systems. Various system parameters (pulse width, guard time, number of pulses transmitted) are used to optimize system performances. The UWB pulse waveform has been designed to better adapt to the characteristics of the transmission channel. The results of this work lay the first rules of energy efficiency engineering design in impulse UWB systems.

Finally, the last part of our work focuses on the pulse design in UWB communication systems. The choice of the pulse shape is very important to improve the system performances and to save energy. The objective is to find the best pulse to minimize energy consumption while ensuring the expected level of performances.

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New Algorithms for Green Wired and Wireless Communications

Abdallah Hamini

En partenariat avec

To my parents

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Résumé étendu en français

Introduction

Avec la croissance fulgurante de l'utilisation des systèmes de communication sans fil et filaires et la forte expansion de l'Internet mobile et services multimédias, l'accès à Internet sans fil et filaires est devenu une partie intégrante et vitale de la société moderne. En conséquence, la demande des nouvelles applications, services et le nombre d'utilisateurs ne cessent de croître. Ces nouveaux services et technologies exigent de plus en plus de ressources. La transmission des données augmente d'un facteur de 10 tous les cinq ans, ce qui provoque une augmentation de la consommation d'énergie de 16 à 20% chaque année. En appliquant ce taux aux réseaux de communication, qui contribuent à plus de 50% de l'ensemble du secteur des technologies de l'information et de la communication (TIC), un grand défi en ce qui concerne les besoins énergétiques des réseaux filaires et sans fil doit être relevé à l'avenir. Actuellement, le secteur des TIC consomme 3% de l'énergie mondiale. Sur ces 3%, l'énergie utilisée pour les systèmes de télécommunications représente 57%.

L'humanité est également confrontée au problème de réchauffement climatique, ce qui peut entraîner des conséquences désastreuses. Ce dernier est principalement causé par les émissions de gaz à effet de serre provenant des activités humaines. Parmi ces gaz émis, le dioxyde de carbone CO_2 est l'un des plus grands contributeurs, principalement générés par l'utilisation de l'énergie. L'émission de CO_2 a fortement augmenté avec la révolution industrielle. Les activités humaines émettent deux fois plus de CO_2 que les processus naturels peuvent absorber. En raison de cette augmentation des émissions de CO_2, il y a un intérêt considérable dans la réduction de la consommation actuelle d'énergie pour le secteur des télécommunications.

Le changement climatique, la hausse des coûts de l'énergie et les contraintes de ressources deviennent des enjeux principaux pour les gouvernements et les entreprises. Ces questions conduisent à des nouvelles tendances dans le développement des technologies vertes. L'étude des communications efficaces du point de vue énergétique nécessitent des investigations dans divers domaines. Dans ce contexte, une gestion efficace de l'énergie grâce à des stratégies d'allocation est essentielle pour mieux exploiter toutes les ressources disponibles sur les réseaux filaires et sans fil. Ces stratégies définissent les règles de partage des ressources afin de minimiser la consommation d'énergie dans les systèmes de communications.

Cette thèse vise à étudier et optimiser les stratégies d'allocation des ressources (temps-fréquence) et la conception d'impulsions afin de minimiser la consommation d'énergie. Les études menées dans cette thèse peuvent être regroupées en trois grandes parties. Dans un premier temps, une étude analytique est menée sur la consommation énergétique pour les réseaux actuels afin d'avoir une vision globale de la consommation d'énergie pour les communications sans fil et filaires. WiMAX et courants porteurs en ligne (CPL) sont pris comme exemples. La seconde partie concerne l'optimisation de l'énergie de la couche physique pour les communications mono et multi-porteuses. Nous proposons une nouvelle approche appelée ultra large temps (ULT) afin de mieux exploiter la consommation d'énergie. Sur la base de cette approche, une nouvelle métrique et de nouveaux algorithmes d'allocation sont définis. Enfin, dans la dernière partie, nous nous focalisons sur la conception d'impulsions pour les systèmes ultra large bande (ULB). Les systèmes actuels utilisent l'impulsion gaussienne pour la transmission. Premièrement les paramètres de l'impulsion gaussienne sont optimisés de façon à réduire la consommation d'énergie. Deuxièmement, nous utilisons des nouvelles formes d'ondes pour les communications ULB afin de minimiser la consommation d'énergie.

Chapitre 1

Radio verte

Introduction

Les initiatives environnementales dans le secteur des télécommunications d'aujourd'hui sont multiples. Deux objectifs des TIC doivent être notés. D'abord la consommation d'énergie dans le secteur des TIC doit être contrôlée. Deuxièmement, exploiter les potentialités des TIC pour aider les autres secteurs à réduire leurs consommation énergétique. Ajoutant à cela, la réduction d'émission de CO_2, le groupe d'experts intergouvernemental sur l'évolution du climat (IPCC) a fixé l'objectif de réduire de moitié les émissions de gaz à effet de serre le plus rapidement possible avant 2050.

Émissions de gaz à effet de serre

Dans les dernières décennies, le monde a connu une forte augmentation des émissions de gaz à effet de serre (le dioxyde de carbone, le méthane, l'oxyde nitreux, ...). Parmi ces gaz émis, le dioxyde de carbone CO_2 est l'un des plus grands contributeurs, principalement généré par l'utilisation d'énergie et représente plus de 84% de ces gaz. La concentration de CO_2 dans l'atmosphère est de plus en plus élevée, l'augmentation d'au moins 35% depuis la révolution industrielle et de 18% depuis 1960. L'humanité transmet 40 GT (gigatonnes) de dioxyde de carbone. Le nouveau rapport de l'agence internationale de l'énergie prevoit une emission d'environ 45 GT de dioxyde de carbone d'ici 2030. Le groupe d'experts intergouvernemental sur le changement climatique (IPCC) prévoit une augmentation de la température moyenne de 1,1 à 6.4°C d'ici 2100. Ce réchauffement est des dizaines de fois plus rapide que ce que l'humanité a connu depuis sa création.

Actuellement, le secteur des TIC représente environ 2% des émissions mondiales de CO_2. Sur ces 2%, le secteur des télécommunications représente 28% d'émissions totales. Les réseaux mobiles sont responsables de 43% du CO_2 émis par le secteur des télécommunications, où le réseau radio est responsable de 80 à 90% d'empreinte CO_2 de l'infrastructure mobile. D'autre part, il est estimé que le secteur des TIC atteint un niveau de 2,6% des émissions mondiales de CO_2 à l'horizon 2020. A cet effet, il y a un intérêt considérable dans la réduction effective de la consommation d'énergie dans le secteur du sans fil, en particulier en Europe. Orange (France), Ericsson (Suède) et Vodafone (Royaume-Uni) veulent réduire considérablement leurs émissions de CO_2 dans une proportion de 20 à 50% d'ici 2020.

Radio verte

L'objectif principal dans les technologies vertes est de fournir de nouvelles techniques pour économiser l'énergie. Les technologies vertes sont des initiatives clés pour de futures applications. Pour caractériser et quantifier la consommation d'un système de communication, il est nécessaire de prendre en compte tous les éléments ou fonctions nécessitant de l'énergie : le traitement de signal, tant à l'émission qu'à la réception, les transducteurs ou les têtes radio fréquences, les relais et d'autres intermédiaires. Une approche véritablement globale de la consommation et de la pollution doit également prendre en compte la fabrication, l'installation, la maintenance et le recyclage des éléments.

Motivations et vision

L'allocation de ressources dans un système de communication est un enjeu important, lorsque l'on cherche à optimiser ses performances. Tout système doit en effet faire face à un certain nombre de limitations physiques et technologiques et des contraintes supplémentaires imposées par les utilisateurs. Cette thèse vise à étudier et optimiser les stratégies d'allocation de ressources. La consommation d'énergie sera intégrée dans les critères d'optimisation. Selon le paradigme proposé par Shannon, un canal de communication peut être divisé en trois blocs, à savoir l'émetteur, le canal de transmission et le récepteur. Dans ce contexte, le travail de thèse se focalise sur la réduction de la consommation d'énergie au côté de l'émetteur. Trois technologies (WiMAX, ULB, CPL) sont examinées et optimisées, afin de répondre à cet objectif ambitieux.

Chapitre 2

Spécifications du système

Introduction

Le deuxième chapitre présente les principales techniques de transmission exploitées dans cette thèse. Tout d'abord, le principe des modulations multi-porteuses, en particulier le concept d'OFDM est détaillé. Puis un aperçu de l'allocation de ressources des systèmes multi-porteuse est décrit, laquelle peut être considéré comme le point départ de nos études. La deuxième partie de ce chapitre est consacrée à la description du système ULB. Enfin, les systèmes considérés dans cette thèse sont présentés. Outre le modèle de canal adopté est également donnée. En outre, la consommation d'énergie pour les systèmes WiMAX et CPL sont fournis.

OFDM

Les techniques de modulations multi-porteuses comme l'OFDM ont été retenues pour assurer des débits de transmission élevés dans les milieux très sélectifs en fréquence. Cette technique permet la transmission des données à haut débit. L'OFDM appartient à une famille de systèmes de transmission appelée modulation multi-porteuses, qui repose sur l'idée de diviser un flux de données haut débit en plusieurs flux parallèles de bas débit. La modulation multi-porteuses permet d'éliminer ou de minimiser les interférences inter-symbole (ISI).

Allocation de ressources

La gestion des ressources au sein d'un système de communications s'impose comme une question de premier plan dès lors que l'on cherche à optimiser ses performances. Dans l'hypothèse d'une connaissance parfaite de la réponse du canal, on peut alors optimiser ces paramètres libres du système en fonction du comportement du canal et des contraintes afin d'assurer un certain niveau de qualité de service. Les ressources qui doivent être gérées dépendent du système mis en œuvre et peuvent être la fréquence, le temps, l'énergie d'émission, etc. L'allocation des ressources peut être considérée comme un problème d'optimisation sous contrainte et est généralement divisée en deux cas : la maximisation de débit (RM) et la maximisation de la robustesse (ROM) ou l'objectif est de, respectivement, maximiser le débit réalisable et la robustesse du système contre le bruit. Dans cette thèse, l'objectif d'optimisation est de minimiser l'énergie pour transmettre une quantité d'information.

ULB

L'ULB est une technique de transmission radio qui consiste à utiliser des signaux s'étalant sur une large bande de fréquences, typiquement de l'ordre de 500 MHz à plusieurs GHz. Une définition aujourd'hui communément admise est que les signaux ULB ont un rapport largeur de bande sur fréquence centrale, ou fractionnel band, au moins égal à 20% ou bien une largeur de bande supérieure à 500 MHz. Aux États-Unis, la FCC a alloué un spectre s'étalant de 3,1 à 10,6 GHz pour les applications ULB sans licence, avec une limite de DSP de -41,3 dBm/MHz sur tout le spectre, alors qu'en Europe l'ECC (European Communications Commission) a imposé une limite de DSP beaucoup plus faible, sauf sur la bande de 6-8,5 GHz. Des mesures similaires sur la puissance d'émission des systèmes ULB ont aussi été prises dans le reste du monde. Ces sévères limitations en puissance ont pour but principal de réduire les interférences avec les systèmes à bande étroite dont le spectre est masqué par celui de l'ULB, tels que l'UMTS, le GSM et le WLAN.

La solution MB-OFDM

La solution MB-OFDM est basée sur une modulation OFDM et une technique multi-bandes qui divise le spectre ULB en 14 sous-bandes de 528 MHz chacune. La plupart des études ont été réalisées sur les trois premières sous-bandes. Les avantages de la solution MB-OFDM résident principalement dans sa faible complexité technique, la modulation OFDM présentant un grand degré de maturité et étant déjà adoptée par plusieurs standards (e.g., DVB-T, DVB-H, ADSL, 802.11a, etc.).

Chapitre 3

ULT Approche : allocation de ressources pour le système OFDM

Introduction

Dans ce chapitre, nous réalisons une étude asymptotique de la consommation d'énergie dans les systèmes mono et multi-porteuses. Les résultats de l'étude permettent de définir la limite asymptotique d'énergie pour transmettre une quantité d'information et conduisent à proposer une nouvelle approche pour les systèmes de communication. Dans la deuxième partie, nous nous focalisons sur l'allocation des ressources pour les canaux parallèles. Les solutions développées visent à proposer la distribution de bits et d'énergie dans les systèmes de communication. Trois cas d'allocation de ressources sont étudiés afin d'obtenir une meilleure efficacité énergétique pour les systèmes multi-porteuses par rapport aux solutions existantes. L'approche proposée d'allocation de ressources peut être utilisée pour tous les modèles de canaux parallèles. Les résultats sont présentés pour les réseaux CPL et WiMAX. De plus, les performances des algorithmes d'allocations proposés sont comparées aux résultats obtenus avec le schéma OFDM conventionnel. Les différents résultats présentés dans ce chapitre montrent une amélioration significative de la consommation d'énergie avec les solutions proposées.

Limite énergétique

Pour économiser l'énergie, l'émetteur et le récepteur peuvent être conçus pour maximiser l'information par unité d'énergie. L'énergie minimum requise est atteinte lorsque le nombre de degrés de liberté est illimité. Le nombre de degrés de liberté est représenté par l'élément fréquence-temps de la formule.

$$J = \left(2^{\frac{Q}{TB}} - 1\right) TBN_0 \tag{1}$$

où J est l'énergie totale nécessaire pour envoyer Q bits, T et B sont le temps et la bande de transmission respectivement. Pour la transmission d'une quantité d'information donnée, avec un temps infini de transmission ou une bande de transmission infinie, le nombre de degrés de liberté tend vers l'infini et l'énergie minimale pour transmettre une quantité d'information est obtenue. Le compromis entre le temps de communication et

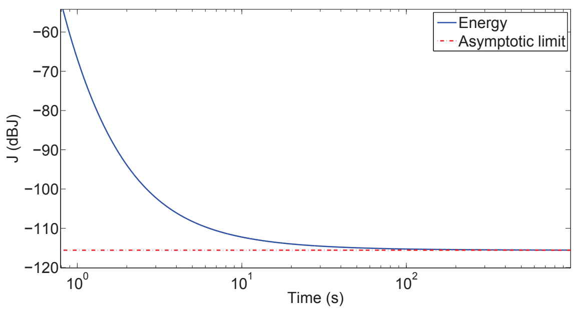

Figure 1: Relation entre l'énergie et le temps de communication

l'énergie est représentée sur la Fig. (1). Dans cet exemple $Q = 1$ Gbit, $B = 50$ MHz. Nous observons que l'énergie diminue lorsque le temps de communication augmente.

Pour réduire l'énergie de transmission, il est nécessaire de transmettre les données sur une longue période de temps que nous définissons comme une nouvelle approche appelée ULT. Par définition, la quantité d'informations et l'énergie réalisées dans un système mono-porteuse ULT sont déterminées par

$$\lim_{T \to \infty} J = QN_0 \log_e 2 \tag{2}$$

Dans un système multi-porteuses ULT, l'énergie est défini

$$\lim_{T \to \infty} J = \frac{QN_0 \log 2}{\max\limits_i |h_i|^2} \tag{3}$$

Pour caractériser la consommation d'énergie des systèmes de communication, nous définissons une nouvelle métrique, appelée efficacité énergétique.

Definition 1 *L'efficacité énergétique est le rapport entre la limite asymptotique d'énergie d'un système et l'énergie consommée par ce système.*

$$J(\beta) = \frac{1}{\beta} N_0 Q \log_e 2 \tag{4}$$

Avec cette définition, β vérifie $0 < \beta \leq 1$. La relation entre l'efficacité énergétique, la quantité d'information et le temps de communication est donnée dans la Fig. (2).

Minimisation du temps de communication

Dans un premier temps, nous proposons de minimiser le temps maximum de communication. L'objectif d'allocation de ressources est alors de trouver la combinaison de

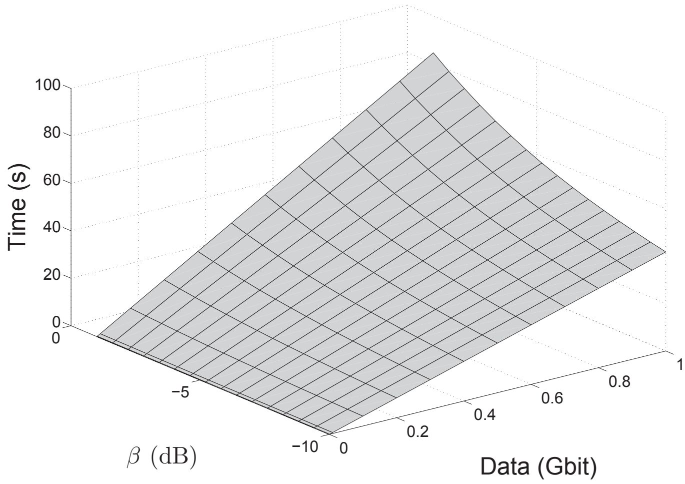

Figure 2: Relation entre l'efficacité énergétique, la quantité d'information et le temps de communication

$\{Qi, Ti\}$ qui satisfait la contrainte d'énergie. Le problème d'optimisation est défini comme suit

$$\min \max_i \; T_i \quad \text{subject to} \begin{cases} \sum_{i=1}^{n} Q_i = Q \\ \sum_{i=1}^{n} J_i = \frac{\lim_{T\to\infty} J}{\beta} \\ Q_i \geq \; 0, \; J_i \geq \; 0 \end{cases} \tag{5}$$

Optimisation du temps cumulé de communication

Avec certains systèmes de communication, il peut être intéressant de minimiser temps cumulé d'occupation des canaux et non pas le temps maximum de communication. L'avantage est de libérer dès que possible les canaux pour d'autres communications. Par exemple, avec une efficacité donnée, le problème est défini par :

$$\min \sum_i \; T_i \quad \text{subject to} \begin{cases} \sum_{i=1}^{n} Q_i = Q \\ \sum_{i=1}^{n} J_i = \frac{\lim_{T\to\infty} J}{\beta} \\ Q_i \geq \; 0, \; J_i \geq \; 0 \end{cases} \tag{6}$$

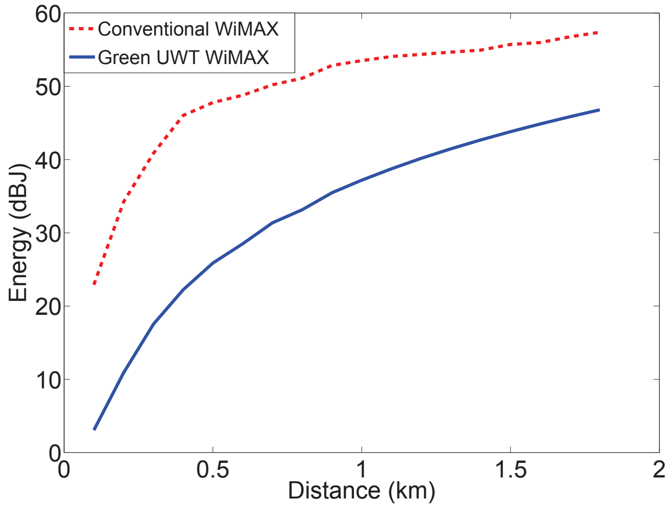

Figure 3: Energie de transmission pour WiMAX

WiMAX

Dans cette section, nous présentons les évaluations numériques à l'aide des paramètres de la norme IEEE 802.16, dans le cas du trafic best-effort. En particulier, notre attention est focalisée sur la comparaison des performances entre l'énergie consommée par le système WiMAX et l'énergie consommée par un système ULT WiMAX proposée dans cette thèse. Dans notre évaluation de simulation, la consommation d'énergie est donnée pour un utilisateur dans une cellule. La quantité d'informations à transmettre est $Q = 1$ Mbit. Avec le système ULT WiMAX, l'optimisation est réalisée sous contrainte de l'efficacité énergétique fixée à-1 dB.

Les résultats de la Fig. (3) montrent que l'énergie utilisée avec le système WiMAX conventionnel est toujours supérieure à celle du système vert ULT WiMAX. Un gain d'environ 20 dB peut être atteint.

CPL

Dans cette section, nous présentons les résultats numériques obtenus avec les paramètres de la norme HPAV pour les réseaux CPL. En particulier, notre attention est focalisée sur la comparaison des performances entre l'énergie consommée par le système CPL et l'énergie consommée par un système ULT CPL proposée dans cette thèse. Avec le système ULT CPL, l'optimisation est réalisée sous contrainte de l'efficacité énergétique

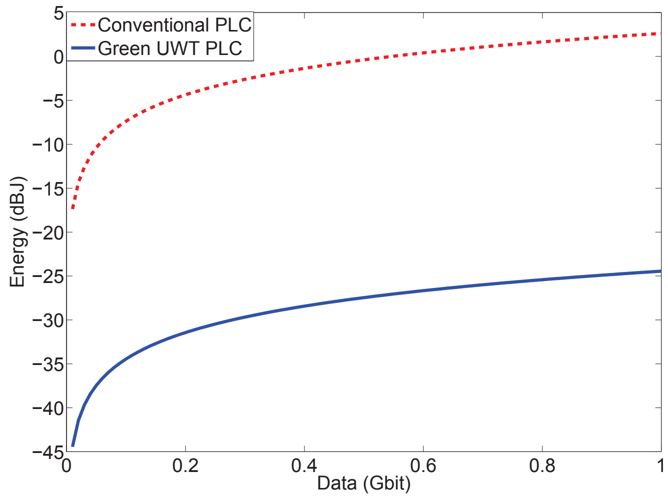

Figure 4: Energie de transmission pour CPL

fixé à -1 dB. Les résultats de la Fig. (4) montrent que l'énergie utilisée avec le système CPL conventionnel est toujours supérieure à celle du système vert ULT CPL. Dans les systèmes CPL, les résultats des simulations montrent que notre système est intéressant pour les applications de transmission de données et les gains énergétiques d'environ 27 dB peuvent être atteints dans les communications CPL avec seulement une multiplication du temps de communication par un facteur de 10.

Chapitre 4

Optimisation des paramètres d'un système ULB

Introduction

Le travail dans ce chapitre se focalise sur les communications ULB. L'objectif principal est de définir les paramètres des systèmes ULB qui minimisent la consommation d'énergie. La première proposition est d'utiliser la forme d'onde des systèmes ULB, puis de déterminer les paramètres optimaux pour la minimisation de l'énergie. Dans ce chapitre, nous nous focalisons sur l'impulsion gaussienne proposée pour les systèmes de communication ULB. Différents paramètres (largeur de l'impulsion T_p, temps de garde T_g, nombre de répétitions d'impulsions L) sont exploitées pour optimiser l'énergie d'un système ULB.

En plus de l'efficacité énergétique, dans la deuxième partie, nous nous focalisons sur la maximisation de la capacité. L'efficacité énergétique est fixée par la métrique d'efficacité énergétique, et la capacité du système est maximisée. La principale approche pour la conception de systèmes ULB est de choisir la durée de symbole plus large que la réponse impulsionnelle du canal, afin d'éviter les interférences inter-symbole (ISI). Cependant, cette approche ne permet pas de maximiser la capacité du système. L'adaptation du temps de garde est un moyen flexible de l'exploitation des ressources du système d'une manière efficace. Le temps de garde optimal est complexe à obtenir. Pour réduire cette complexité, une nouvelle méthode d'optimisation est introduite. Ce procédé d'optimisation définit des nouveaux paramètres qui fournissent des performances très proches des performances optimales du système. Ces paramètres lient le temps de garde aux caractéristiques du canal avec des équations simples. L'adaptation du temps de garde est directement basée sur ces paramètres. Les résultats de simulation sont effectués pour les communications ULB sur les canaux WiMedia. Dans la dernière partie de ce chapitre, nous nous focalisons sur l'allocation de ressources pour les systèmes multi-bandes. Le problème de minimisation d'énergie est présenté et des nouveaux algorithmes sont proposé pour les systèmes multi-bandes.

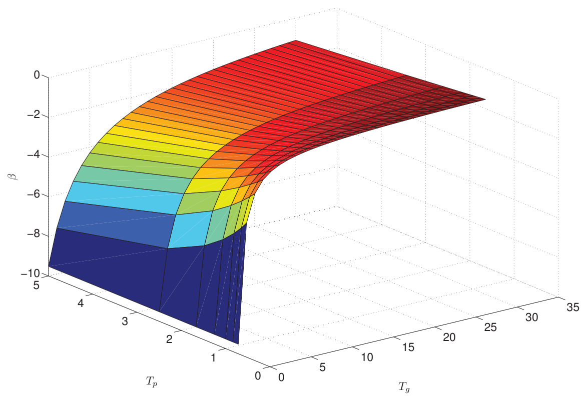

Figure 5: Relation entre l'efficacité énergétique, le temps de l'impulsion et le temps de garde

Paramétre du systéme ULB

L'objectif de l'allocation de ressources est de trouver la combinaison de $\{T_p, T_g, L\}$ qui satisfait l'efficacité énergétique et maximise le débit binaire. Le problème d'optimisation est

$$\min T_b \quad \text{subject to} \;\; J = J(\beta) \;\; . \tag{7}$$

Plusieurs combinaisons de $\{T_p, T_g, L\}$ donnent la solution du problème (7). La Fig. (5) montre l'efficacité énergétique par rapport aux différents paramètres du système.

Qualité de service et l'efficacité énergétique

En plus de la réduction de consommation d'énergie, la qualité de service (QoS) qui correspond au taux d'erreur binaire (TEB) doit être garantie. La contrainte TEB est utilisée pour le système d'optimisation afin d'éviter toute perte inutile de paquets et de garantir un certain niveau de qualité de service. En outre, l'optimisation du système devient

$$\min T_b \quad \text{subject to} \begin{cases} J = J(\beta) \\ TEB_i = TEB_a \end{cases} \tag{8}$$

où TEB_i est le TEB moyen, et TEB_a est la contrainte de TEB moyen. Dans le cas d'une modulation BPSK, la formule approximative de TEB est

$$TEB_i = Q(\sqrt{2E_b/N_0}) \tag{9}$$

La nouvelle optimisation fournit les valeurs optimales du système sous contraintes de TEB et d'efficacité énergétique.

Optimisation de la capacité

L'impulsion gaussienne a été initialement proposée et a été largement utilisée pour les applications ULB. La durée de symbole système ULB est généralement large de telle sorte que l'interférence entre symboles soit négligée. Cependant pour maximiser la capacité, le système n'a pas nécessairement besoin d'un temps de garde très large. Autrement dit, le système peut tolérer une quantité d'interférence afin de réduire le temps de garde, et la capacité du système peut être augmentée. L'adaptation du temps de garde permet l'exploitation des ressources de manière efficace. Dans ce chapitre, nous présentons une analyse du problème d'optimisation de temps de garde. Le problème d'optimisation est complexe et nécessite un temps de calcul important. Le développement d'une nouvelle méthode d'optimisation pour réduire la complexité du système et améliorer la capacité d'adaptation de temps de garde est nécessaire. Une des méthodes efficaces consiste à définir de nouveaux paramètres qui fournissent des performances très proches à la configuration optimale. Ces paramètres relient le temps de garde aux caractéristiques du canal avec des équations simples. Trois mesures du canal sont considérées. Ces mesures sont la moyenne quadratique (RMS) de retard du canal, l'énergie reçue et l'utilisation de la formule de la capacité. Ce choix est motivé par le fait que ces mesures peuvent être obtenues facilement dans les systèmes de communication. Le procédé d'optimisation fournit la valeur des paramètres qui seront utilisés directement dans les systèmes pratiques. Ces valeurs des paramètres facilitent le calcul du temps de garde et évitent ainsi le coût associé à l'optimisation du temps de garde. Le temps de garde peut être flexible et adapté par cette méthode pour n'importe quel canal.

MB-OFDM

La division en sous-bandes permet un meilleur contrôle de l'occupation spectrale du signal émis. Deux modèles d'allocation de ressources sont étudiés. Le premier modèle d'allocation (Algorithme 2) choisit les sous-bandes adjacentes. Dans le second modèle d'allocation (Algorithme 3), les meilleures sous-bandes sont choisies en fonction de la réponse du canal. Dans la Fig. (6), l'efficacité énergétique est tracée en fonction de temps de bit. Pour la même valeur de l'efficacité énergétique, l'algorithme 3 fournit la

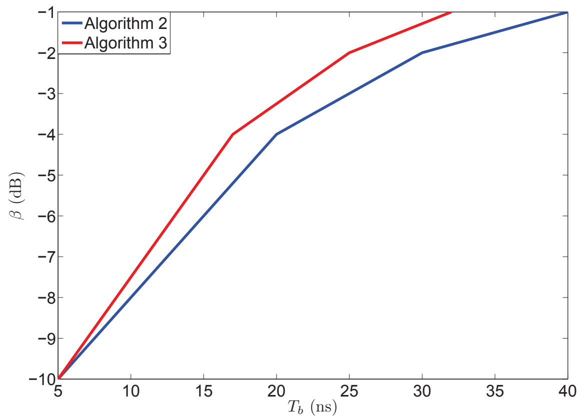

Figure 6: la relation entre le temps de bit et l'efficacité énergétique

durée minimale de bit. Cet algorithme nécessite moins d'énergie pour le même débit binaire.

Chapitre 5

Conception des impulsions

Introduction

Dans les systèmes de communications, nous pouvons utiliser d'autres impulsions avec le nouveau défi de la radio verte, les nouveaux systèmes de communication ULB ont besoin de concevoir une nouvelle forme d'onde afin d'atteindre une consommation d'énergie optimale. Ce chapitre traite le problème de la conception de l'impulsion ULB. La question principale ici est de concevoir une impulsion sans assumer une forme d'onde de base. Dans ce chapitre, nous étudions diverses impulsions qui consomment moins d'énergie que l'impulsion gaussienne . Deux impulsions d'émission dans les communications ULB sont proposées. Chaque impulsion apporte une amélioration en termes d'efficacité énergétique. Dans un premier temps, l'impulsion est optimisée dans le cas d'un récepteur à filtre adapté. Par ailleurs, une amélioration à cette impulsion est également fournie. Deuxièmement, nous ne nous limitons pas au récepteur à filtre adapté. Notre approche consiste à obtenir la meilleur impulsion d'émission dans le cas général. Une nouvelle impulsion est alors donnée dans ce chapitre.

Retournement temporel

L'objectif de cette section est de trouver l'impulsion qui maximise le rapport signal sur bruit dans le cas du récepteur à filtre adapté. Une impulsion sous-optimale a été trouvée en appliquant l'inégalité de Cauchy-Schwarz. Cette solution conduit à l'utilisation de l'impulsion de retournement temporel. L'impulsion de retournement temporel fournit les meilleures performances en termes de TEB et de la capacité pour une valeur fixe de Eb/N0. Le gain entre les deux impulsions est supérieur à 3 dB. Comme dans la Fig. (7), un facteur de gain de 50% en termes d'énergie est alors atteint avec l'impulsion de retournement temporel. Cette impulsion permet des gains d'énergie dans les systèmes de communication avec les mêmes performances.

Impulsion optimale

Dans cette section, notre objectif est de définir l'impulsion optimale pour un système de communication. Pour établir une formulation plus explicite de minimisa-

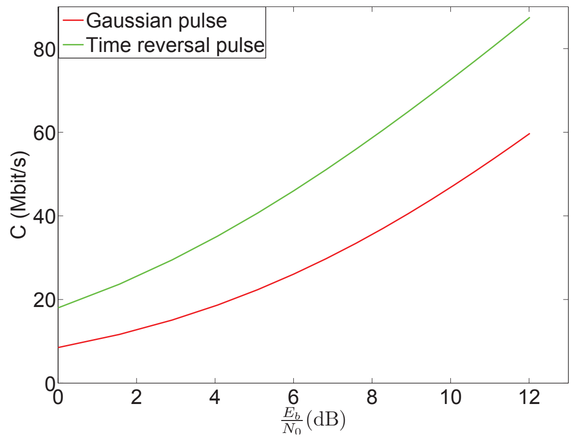

Figure 7: Performances de l'impulsion gaussienne et l'impulsion de retournement temporel pour les différents valeurs de $\frac{E_b}{N_0}$

tion de l'énergie, nous expliquons ici la formulation de problème d'optimisation. Dans ce chapitre, nous essayons de trouver l'impulsion qui minimise l'énergie au niveau d'émetteur pour SNR cible. La solution est formulée dans le cas général. Le problème d'optimisation est

$$\min \quad E_b \quad \text{subject to} \quad \frac{\sum_{i=0}^{N_x-1}\left(\sum_{j=0}^{N-1} f_j h_{i-j}\right)^2}{\sigma^2} = SNR \tag{10}$$

avec f la forme d'onde, h le gain du canal et E_b l'énergie de bit. La solution du problème (10) conduit à l'utilisation d'une nouvelle forme d'onde appelée l'impulsion optimale. Cette nouvelle impulsion permet un gain d'énergie considérable dans les systèmes de communication avec la même valeur de SNR. Pour la même valeur de la capacité du système, le facteur de gain de 7,85 dB de l'énergie est atteint. Ce gain s'explique par le fait que la nouvelle impulsion est mieux adaptée aux conditions de transmission que l'impulsion gaussienne .

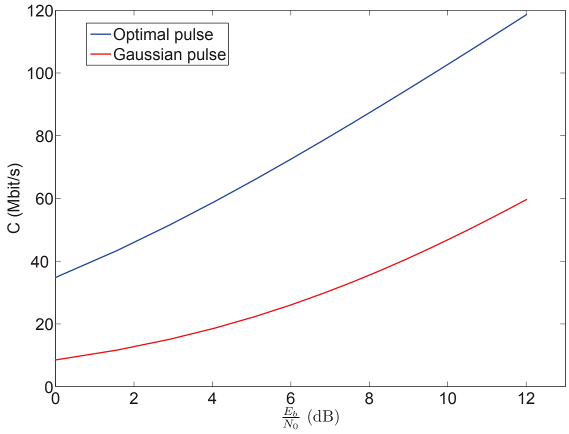

Figure 8: Performances de l'impulsion gaussienne et l'impulsion optimale pour les différents valeurs de $\frac{E_b}{N_0}$

Conclusion

Cette thèse a principalement étudié l'allocation de ressources et les stratégies de conception d'impulsions afin de minimiser l'énergie des systèmes mono et multi-porteuses. Une nouvelle approche a été proposée pour les systèmes de communication visant à minimiser l'énergie. Ainsi, nouvelle métrique d'efficacité énergétique est définie. Des algorithmes d'allocation de ressources ainsi que des algorithmes d'ajustement des paramètres du système sont proposés. Finalement, une nouvelle forme d'onde est proposée pour la minimisation de l'énergie dans les systèmes ULB.

Les deux premiers chapitres ont été consacrés à la présentation du contexte de l'étude et les spécifications des systèmes mis en place. Le premier chapitre nous a donné l'occasion de se familiariser avec le sujet de l'étude. Nous avons d'abord présenté le secteur des TIC, son impact et son importance dans la société moderne. Après, nous avons présenté un aperçu général des technologies vertes. Les développements récents dans le secteur des TIC ont également été mis en évidence avec une description des différentes tendances et solutions pour l'amélioration de la consommation d'énergie des systèmes sans fil et filaires. Dans le deuxième chapitre, les technologies WiMAX et CPL ont été décrites en mettant l'accent sur les principales caractéristiques des canaux de transmission. D'autre part, nous avons présenté les principales techniques de transmission que nous traitons dans cette thèse, principalement les systèmes OFDM, ULB.

Le Chapitre 3 a principalement été focalisé sur le problème d'optimisation de l'énergie. Nous avons examiné le problème de consommation d'énergie dans un contexte mono-utilisateur pour un système mono et multi-porteuses. La limite asymptotique de la consommation d'énergie pour les deux systèmes a été fournie. Une nouvelle approche, appelée ULT, et une nouvelle métrique de l'efficacité énergétique a été proposée et définie pour réduire l'énergie. L'utilisation de l'approche ULT fournit la borne inférieure de la consommation d'énergie transmise. Des nouveaux algorithmes d'allocation de bits et d'énergie ont été développés. En outre, les performances de ces allocations ont été comparées avec l'approche conventionnelle des systèmes WiMAX et CPL.

Dans le chapitre 4, nous avons étudié l'aspect de la conception d'impulsions ULB dans les systèmes de communication. Ce chapitre a été divisé en trois parties. Dans la première partie, nous nous sommes focalisés sur la minimisation de l'énergie. L'objectif principal était d'obtenir les paramètres optimaux du système pour une efficacité énergétique cible donnée. Le chapitre 4 introduit une toute nouvelle façon pour le choix des paramètres du système, où la consommation d'énergie du système est réduite au minimum. Dans la deuxième partie du chapitre 4, une étude théorique a été réalisée afin de maximiser la capacité d'un système ULB. Nous avons montré que l'utilisation d'un temps de garde adapté aux conditions de transmission est bénéfique en termes de capacité du système. Un système de faible complexité pour sélectionner le temps de garde est introduit. Dans la dernière partie de ce chapitre, nous nous sommes focalisés sur les communications MB-OFDM. Deux nouveaux algorithmes d'allocation de ressources sont proposés afin d'augmenter l'efficacité énergétique du système.

Dans le chapitre 5, deux impulsions ont été proposées, l'impulsion de retournement temporel est utilisée dans un premier temps. Dans un second temps une impulsion optimale en terme d'efficacité énergétique pour les communications ULB est proposée. Il a été montré que les impulsions proposées offrent un gain significatif en termes de capacité des systèmes ULB.

List of Figures

List of Tables

Acronyms

ADC	Analog-to-Digital Converter
ADSL	Asymmetric Digital Subscriber Line
AMC	Adaptive Modulation and Coding
BER	Bit-Error-Rate
BPSK	Binary Phase-Shift Keying
CDF	Cumulative Distribution Function
CMOS	Complementary Metal Oxide Semiconductor
CPE	Customer-premises equipment
DC	Direct Current
DSL	Digital Subscriber Line
DVB-T	Digital Video Broadcasting-Terrestrial
FCC	Federal Communications Commission
GSM	Global System for Mobile Communications
HPAV	Home Plug AV
HPAV BPL	HomePlug Broadband Power Line
HV	High Voltage
ICT	Information and Communication Technology
IPCC	Intergovernmental Panel on Climate Change
ISI	Inter-Symbol Interference
KKT	Karush Kuhn Tucker
LAN	Local Area Network
LCA	Life Cycle Assessment

LOS	Line-of-Sight
LTE	Long Term Evolution
LV	Low Voltage
MA	Margin Adaptive
MAC	Media Access Control
MB-OFDM	Multi-Band-Orthogonal Frequency Division Multiplexing
MCS	Modulation and Coding Scheme
MIMO	Multiple-Input Multiple-Output
MV	Medium Voltage
NLOS	Non Line-of-Sight
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
PDF	Probability distribution function
PUSC	Partial Use of Sub-Carriers
PLC	Power Line Communication
PSD	Power Spectral Density
QoS	Quality of Service
RF	Radio Frequency
RA	Rate Adaptive
UWB	Ultra Wide Band
UWT	Ultra Wide Time
SNR	Signal-to-Noise Ratio
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network
WPAN	Wireless Personal Area Network

Introduction

With the explosive growth in the use of wireless and wired communication systems and the strong expansion of mobile Internet and multimedia services, wireless and wired Internet accesses have become an integral and vital part of modern society. Many of our daily activities mobilize a part of the wireless and wired networks. As a result, the demand for new applications, services and the number of users is steadily growing. These new services and technologies demand more and more of resources.

Due to increasing demand of data traffic rates and rollout of advanced communication systems, an exponential surge of energy consumed by telecommunication industry has already occurred in recent years. The data transmission is increasing by a factor of 10 times every five years, causing an increase in energy consumption of 16 to 20% every year. Applying this rate to communications networks, which contribute more than 50% of the entire information and communications technologies (ICT) energy footprint, a great challenge regarding the energy requirements of wired and wireless networks is expected in the future.

The humanity is also facing another urgent problem of global warming, which may cause disastrous consequences. It is mainly caused by the emission of greenhouse gases coming from human activities. Among these emitted gases, carbon dioxide CO_2 is one of the greatest contributors, mainly generated by energy utilization. Human activities emit twice more of CO_2 than natural processes can absorb. The emission of CO_2 has risen sharply with the industrial revolution and eventually will rise significantly if the industries do not take precautions. Currently, the ICT sector represents 2% of global CO_2 emissions (around the same percentage as that of the air traffic and about one fourth as that of the road traffic) and consumes 3% of global energy. Out of this 3%, the energy used for telecommunication systems represents 57%. On the other hand, it is estimated that the ICT sector will reach a level of 2.6% of the global CO_2 emission around 2020. Due to this increase in CO_2 emission, there is a considerable interest in reducing current energy consumption in the telecommunications sector within the green communications context.

Climate change, rising energy costs and resource constraints are becoming main issues for governments and businesses. These issues drive new trends in the development of green technologies. These new green technologies are supported by both public and private sectors. Green technologies are key of future applications. The study of green communications will require investigations in various areas such as efficient medium access channel protocols, frequency reuse strategies, spectral policy and new performance metrics. In this context, effective management of energy through allocation strategies is essential to better exploit all the available resources on the wireless and wired networks. These strategies define the rules for sharing resources in order to minimize consumption energy and satisfy the multiple constraints.

Thesis overview and contributions

This work was carried out at the Institute of Electronics and Telecommunications of Rennes (IETR) in the National Institute of Applied Sciences (INSA-Rennes) and the University of Udine (Italy). This thesis aims to study and optimize resource allocation strategies (time-frequency) and pulse design to minimize the energy consumption.

The studies in this thesis can be grouped into three main parts. The first part is devoted to have a global vision for energy consumption for wireless and wired communications. WiMAX and power line communication (PLC) networks are taken as examples. The objective is to see the current state of energy consumption in communication systems.

The second part concerns the optimization of the energy of physical layer for single and multi-carrier communications. We propose a new approach called ultra wide time (UWT) to better exploit the energy consumption, which is the first original contribution of this thesis. Based on this approach, new algorithms for resource allocation and performance metrics are defined. The system is analyzed in single carrier and multi-carrier contexts. Compared to existing methods of allocating resources for multi-carrier systems, we see that this solution can greatly improve the energy efficiency of the systems.

Finally, in the last part, we focus on pulse design for ultra wide band (UWB) systems. The objective of this part is to explore the different pulses in conjunction with various resource allocation and optimization schemes to consume less energy in communication systems. Current systems use the Gaussian pulse for transmission. In the beginning the system parameters of Gaussian pulse are optimized so as to reduce the energy consumption. New system parameters algorithms are then proposed and analyzed for UWB communications. This is the second original contribution of this thesis. Secondly, we define a new pulse waveform for UWB communications proposed in order to minimize the energy consumption. This is the third original contribution of this thesis. The pulse proposed can greatly improve the energy efficiency of the system.

This dissertation is organized as follows. Chapter 1 specifies some of the fundamental aspects of ICT. An overview of green radio is given. The first part of this chapter provides a historical overview of ICT, discusses on the energy consumption of ICT and lists the main green solutions. The future challenges of telecommunication are also considered in this chapter. Finally, the context of the study is presented.

Chapter 2 describes the main transmission techniques exploited in this thesis, mainly the multi-carrier modulation. An overview of conventional orthogonal frequency division multiplexing (OFDM) systems is given. The impulse and multi-band UWB principle is also elaborated in this chapter. Finally, the considered systems in this thesis are presented. This chapter also discusses the resource allocation optimization. An introduction to energy consumption is given followed by the description of fundamentals of resource allocation and optimization for multi-carrier systems. Different resource allocation strategies are presented. The energy consumption for WiMAX and PLC systems are provided.

Chapter 3 presents the resource allocation principles and optimization strategies, namely, the energy minimization. A survey key results from information theory is given. Therefore, an asymptotic study for energy consumption in single and multi-carrier systems is realized. The results of study permit to define the limit of energy consumption for data transmission. A new approach of communication systems is proposed. This approach provides a basis for the development of other resource allocation solutions, especially those based on the energy efficiency metric criterion. Furthermore, the resource allocation for parallel channels are developed. Three cases of resource allocation are studied in order to obtain better energy efficiency for multi-carrier systems in comparison to existing solutions.

Chapter 4 is devoted to pulse design aspect of UWB systems. The major question for the first part of chapter is: what is the optimal system parameters to minimize energy. The first proposition is to use the shape of impulse UWB systems and then to determine the best parameters for the energy minimization. This chapter focuses on Gaussian pulse proposed for UWB communication systems. Furthermore, in the second part, the system capacity maximization is developed. The energy efficiency is fixed by the metric, and the system capacity is maximized. The last part of this chapter focuses on multi-band allocation. The energy minimization problem is presented and a new algorithm is introduced for multi-band allocations.

Chapter 5 presents the global pulse design optimization for UWB communications. The main question solved is how to design a pulse without assuming a particular set of basis signals. Various pulses shaping that consume less energy than Gaussian pulse are proposed.

Finally, in the general conclusion of the thesis, we summarize this dissertation and draw some perspectives of this work. Some recommendations are also proposed for future research works.

List of publications and reports

Journal Papers

- A. Hamini, J.-Y. Baudais, A.M. Tonello and J.-F. Helard "Guard time optimization for capacity maximization of UWB communications", to be submitted.

- J.-Y. Baudais, A. Hamini and A.M. Tonello "Energy efficiency in parallel independent channels", to be submitted.

International Conferences

- A. Hamini, J.-Y. Baudais and J.-F. Helard "Best effort communications with green metrics", in IEEE Wireless Communications, Networks Conference, (Cancun, Mexico), pp. 1346-1351, March 2011.

- A. Hamini, J.-Y. Baudais, and J.-F. Helard "Green resource allocation for powerline communications", in IEEE International Symposium on Power Line Communications and Its Applications, (Udine, Italy), pp. 393-398, April 2011.

National Conferences

- J.-Y. Baudais, A. Hamini et J.-F. Hélard "Efficacité énergétique pour les communications vertes", in Colloque GRETSI, (Bordeaux, France), September 2011.

Reports

- A. Hamini "Deployment of monocyle pulse in UWT" rapport GDR-ISIS, Septembre 2010.

- A. Hamini "Pulse design and resource allocation in UWB communication" rapport UEB (université européenne de Bretagne), October 2011.

Chapter 1

Green radio

In a context where the energy demand is growing continuously, it becomes important for all sectors to take into account the problem of energy consumption and the ICT sector is not exempt. The energy consumed by wireless and wired networks is not negligible. However, it is insufficiently considered for actual networks. This first chapter aims to present the context of the study.

The first part describes the ICT sector, its origin and scope of deployment. Thus, after some historical information, we focus on the future and emerging technologies. The energy consumption in ICT sector is then discussed. We provide some statistics for energy consumption, and the impact of environment. An overview of green technologies is then proposed, followed by motivations and the solutions for future green networks. The last part describes the motivations and visions of the thesis.

1.1 ICT development

Before considering the link between ICT and energy, and in particular between ICT and sustainable development, it is important to define the term ICT and to understand the social and technological environment in which they grow. ICT today comes from the marriage of computers, electronics, telecommunications and broadcasting. The use of ICT continues to expand and new technologies contribute every day. The acronym ICT was used for the first time by academic researchers in 1980 [2], but it's more cited being used in UK government report [3]. Information and communication technologies include all technologies that enable the processing of information and facilitate different forms of communication among human actors, mainly information technology, Internet and telecommunications. ICT are a set of resources to manipulate information and especially computers, programs and networks needed to convert, store, manage, transmit and retrieve information. ICT can be grouped into a few sectors: computer equipments, servers, hardware, microelectronics and components, telecommunications and computer networks. The modern technologies of information has gone through important stages before coming to the current state of technology advancement. Up to now, the constraints (speed, capacity and reliability of information) have gradually progressed.

The real revolution in the ICT sector began by the invention of Internet and the mobile phone. Then, technological innovations, coupled with lower costs and competition, contrary to all expectations, provoked an explosion of mobile telephony. New networks are spread for internal and external connection and a territorial development of digital technology for broadband Internet is developed. In fact, these tools feature new services in terms of access to information. Mobile communications systems revolutionized the way people communicate, joining together communications and mobility. A long way in a remarkably short time has been achieved in the history of wireless. This convergence is not only a technological revolution but also marketing. The progress of information society is based on the success of information technology which has been made possible by innovations in microelectronics. In the last years, ICT systems have allowed the enormous economic improvement [4]. The technologies of information and communication gradually penetrate all fields of economic and social activities. ICT is widely recognized for its essential role in transforming the economy and society. In the last decade, with the expansion of Internet, the use of ICT has been increased and a majority of the people are using these tools to access information. On the other hand, the number of available services have exploded and the ICT sector has become an integral and vital sector for humanity. ICT now plays an increasingly important role in the advancement and operations of many fields such as manufacturing, transport systems, medical science, government departments, the arts, businesses of all sizes and shapes. ICT is being deployed and utilized in many sectors to carry out a wide range of tasks.

The wireless and wired communication is one of the most vibrant areas in the ICT field today. This is due to several factors. First, there has been an explosive increase in demand for connectivity, driven so far mainly by cellular telephony [5]. Second, the enormous progress in integrated circuits has enabled small area and low power implementation of sophisticated signal processing algorithms and coding techniques. Third, the success of second-generation (2G) digital wireless standards in particular provides a concrete demonstration that good ideas from communication theory can have a significant impact in practice. Rarely have technical innovations changed everyday life as fast and profoundly as the massive use of the Internet and introduction of personal mobile communications. The last decade has witnessed a phenomenal growth of subscribers in both wireless and wired technology. There has been a clear shift from fixed to mobile cellular telephony. The first Global system for mobile communications (GSM) phone call took place 1991 in Finland. Only 20 years later there were over 3 billion GSM users [5]. During the last few years, more than 60% of people on this planet possessed a mobile telephone [5]. On the other hand, the number of Internet servers has increased by a factor of 1000 [6]. Internet appears in the 80s and now has more than 2 billion users [6].

These two developments have, and continue to evolve strongly. The data transmission rates both in the wired and wireless networks have been increasing by about a factor 10 every 5 years [4]. In order to fit this exponentially rising, the capacity of storage devices and the processing power double approximately every 18 months.

1.2 Future technologies and challenges

The increasing ICT dimension is also an important element in the context within which the future and emerging technologies will operate. Telecommunication sector constitutes a major sector of ICT and is undergoing an enormous growth. Capacity issues and delivery of complex real time services are some of the main concerns that yield high power consumption patterns. In this section, we will not detail enough the importance of the other sectors ICT, but we focus on telecommunication improvements and the applications of tomorrow.

The quantity of information transmitted currently to individuals and organizations is unprecedented in human history, and the rate of information generation continues to grow exponentially. The last decade witnessed more and more the use of new techniques and technologies to improve the rate of information transmission. Both wired and

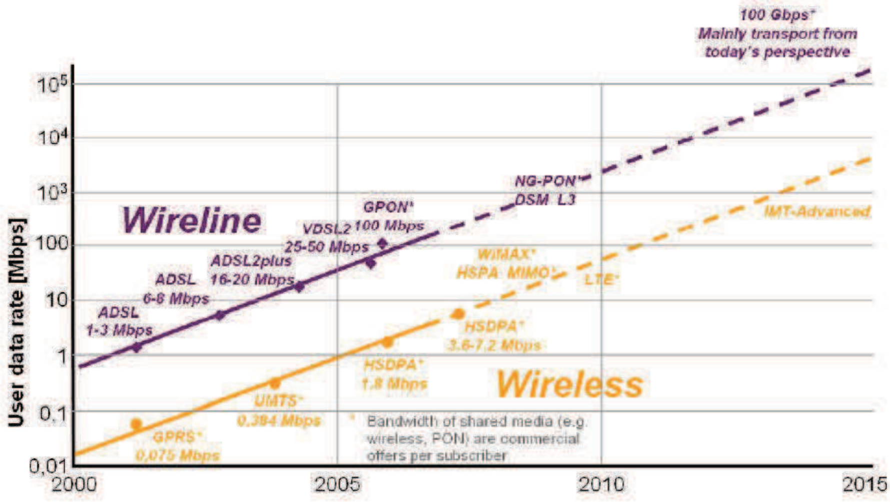

Figure 1.1: Technologies evolution [1]

wireless sectors are improved in this way. Fig. 1.1 shows the evolution of user data rate in both sectors during the last decade.

The wired communications saw a large increase in bit-rate with the use of optical fibers. The emergence of new technologies in communication systems and also the ever increasing growth of user demand have triggered industries to come with the fourth generation mobile communication system. The major expectation from the 4G wireless communication networks is to be able to handle much higher data rates, which will be in the range of 1 Gbit/s in the wireless local area network (WLAN) environment and 100 Mbit/s with cellular networks. A user, with a large range of mobility, will access the network and will be able to seamlessly reconnect to different networks, even within the same session. The spectral allocation is expected to be more flexible, and even flexible spectral sharing among the different networks is anticipated.

In the last decade we are witnessing more and more the existence of the wireless communications and as a consequence the need to develop more these technologies. The current technologies are the merging of voice, data, video, image and wireless communications technologies with PC and microelectronic technologies to facilitate communications between people or to deliver information, entertainment, and other services to people. Due to the success and strategic importance of these technologies, some challenges and ways for future technologies are proposed and begin to be investigated.

First, the challenge of flexible and intelligent networks is considered. The concept of flexible radio will play an important role in mobile communications in the future. It is to be reconfigured by software radio systems and dynamically, in order to live the standards of many current and future communication systems (eg, WiMAX and Long term evolution, LTE) within the same equipment, optimize the use of radio resources and reduce the specific hardware [7].

Second, the cost challenge for new ICT technologies is expected to have an impact on both professional and personnel lives. However, advances in transmission technology alone may not be sufficient to support the anticipated demand for higher data rates and greater traffic volumes. Fortunately, a low cost means of increasing capacity is to match wireless infrastructures to the non-uniform spatial distribution of traffic. Multiple radio access standards and base station classes, having different cost and performance, could be combined to create a heterogeneous wireless access network. To support high data rates with wide area coverage at a low cost would require substantial technological advances though [8].

Last but not least, ICT technologies are expected to achieve substantial efficiency gains of energy as well as reduce the greenhouse gases emissions. This incorporates the ICT contributions to the public-private partnerships on energy efficiency for all technologies. Characteristic examples are green networks, energy efficient electronics and the application of embedded systems towards low carbon and energy efficient technologies [1]. Thus, the work of the thesis is subscribed in this way.

1.3 Energy consumption in ICT

1.3.1 ICT consumption

With the explosive growth in the use of communication systems and the rapid expansion of the Internet in the world, the demand for new applications, services and the number of users is growing steadily. But according to the basic principles of information theory, the energy consumption is expected to increase significantly with increasing bit-rate. An exponential surge of energy consumption of ICT industry has already occurred in recent years. The great challenge regarding energy needs of communication system is expected in the future. In this section, we present some statistics on energy consumption in the ICT sector, and more specifically in the telecommunication field. The

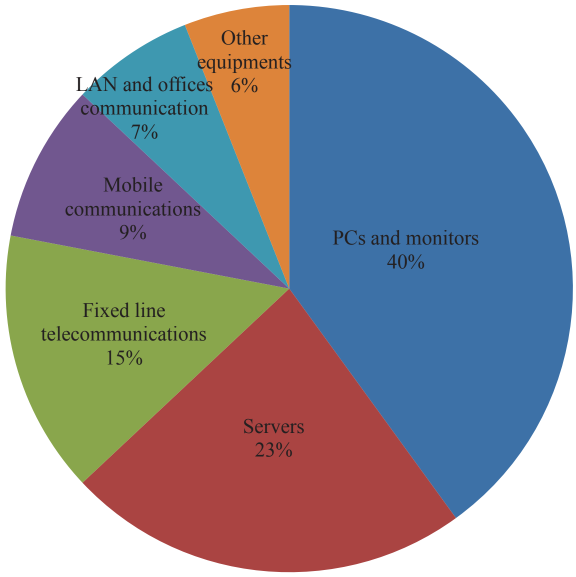

Figure 1.2: Energy consumption in ICT

energy demand of ICT is growing much faster than the total energy demand. Growth in energy consumption is 16% to 20% per year in the field of ICT [1]. In France, the power consumption is between 55 and 60 TWh per year, or 13.5% of the electricity consumption by end-use applications [9]. Taking into account the end use equipment and its related infrastructure (servers, routers, switches for the Internet, base station switching units and others for telecommunication), typical calculations for an industrialized country suggest that ICT accounts for about 3% of total electricity demand [10, 11]. This is comparable to the energy consumption of the aviation industry. If we incorporate the entire life cycle, the share of ICT is closer to 4% of total electricity [12]. The exponential growth of ICT, which will be required for reducing the energy intensity of the entire economy, is currently not sustainable. Fig. 1.2 shows the energy consumption of different sectors of ICT. The PCs and monitor are responsible of 40% of energy consumption in ICT sectors. The growth rate for PCs energy consumption worldwide is expected to be somewhat about 7.5% per year [13]. This is mainly caused by the growing number of PCs that are used worldwide (growing by about 10%) and the ever rising data volumes to be processed by a PC.

The operation of telecommunication networks (including the operation of servers, mobile networks, WLANs, LANs and fixed line networks) represents 50% for ICT consumption. For network equipment, the energy consumption growth rates are typically about 12% per year. Especially the growing wireless access infrastructure (for mobile phones, wireless computer access, etc.) and the quick rise in home networks are responsible for steeply growing energy consumption rates. This considerable growth is mainly caused by the ever growing data volumes to be processed, stored and accessed, and the associated power for cooling.

The analysis of the energy consumption in telecommunication networks, must make a distinction between the customer premises equipment (CPE), core networks and access networks. CPE is equipment that is in the customer site (a firm) and is connected to the infrastructure of an operator in a point of presence via a local loop. CPE generally refers to devices such as telephones, routers, switches, home networking adapters and Internet access gateways that enable consumers to access communications service providers. Core networks are the Internet highways of the telecommunication networks. They are built to interconnect different sites and aggregate the traffic between these sites. They typically have a mesh structure. Core networks are built on many levels covering areas ranging from small cities to global networks. Access network is that part of a network which connects subscribers to their immediate service provider. They are typically built in a tree structure. We distinguish fixed access networks in which the user is connected to the network by a cable and wireless access networks which use radio waves. In [14], the distribution of the network power consumption of a typical operator is provided. It shows that half of the operational power consumption is used for the fixed line access network and about one fifth for the mobile access network. The aggregation and backbone networks represent a much smaller fraction. For wireless communications, the significant environmental impact is due to the high energy consumption in cellular base stations. There are 4 million base stations and around 3 billion subscribers worldwide [15]. The energy consumed by the base stations accounts for 80% of the energy used by operators [10].

Currently the 3G base stations use powers very inefficiently because of linear RF power amplifiers [10]. In [10], the energy consumed by the second and third generations networks are provided. Note that the power consumed by 3G networks is 5 times larger than the power consumption of second generation networks. The telecommunication industry is seeking to improve the energy efficiency of its latest generation of base stations, ensuring adequate low levels of energy consumption. On the other hand, processor power consumption has increased by over 200% every four years, while battery energy density has increased by a modest rate of 25% [16].

This thesis reviews the range of access network technologies for networks access broadband. We focus here on the energy consumption of WiMAX, PLC and UWB communications.

1.3.2 Greenhouse gas emissions

In recent decades, the world has experienced a large increase in emissions of greenhouse gases (greenhouse gas: carbon dioxide, methane, nitrous oxide,...). Among these emitted gases, carbon dioxide CO_2 is one of the greatest contributors, mainly generated by energy utilization and represents more than 84% of these gases [17]. Human activities emit twice more CO_2 than natural processes can absorb [4, 17, 18]. The emission of CO_2 has risen sharply with the industrial revolution and it is likely to increase significantly if the industries do not take precautions. Fig. 1.3 shows the level of CO_2 emissions in the last two centuries. The concentration of CO_2 in the atmosphere is the highest it has been in the last years, increasing by at least 35% since the industrial revolution and by 18% since 1960. Actually, humanity transmit 40 GT (giga tonnes) of carbon dioxide [19]. The new report of the international energy agency projects that by 2030 the world will be emitting about 45 GT of carbon dioxide. The humanity is also facing another urgent problem of global warming, which may cause disastrous consequences. It is mainly caused by the emission of greenhouse gases coming from human activities [1, 20]. The green house gases exist for most natural state. But human activities, particularly the overconsumption of energy, emit significant amounts each year, helping to destabilize the global climate. Intergovernmental panel on climate change (IPCC) scenarios presented in Paris in February 2007 forecasted an increase of average temperature of 1.1 to 6.4°C by 2100 and analyzed some of the consequences [21]. This warming is tens of times faster than what humanity has known since its inception. The consequences of global warming, which are likely to increase and extend, can be burdensome for humanity. Scientists have warned that global warming has a negative impact on global health, society and economy [20].

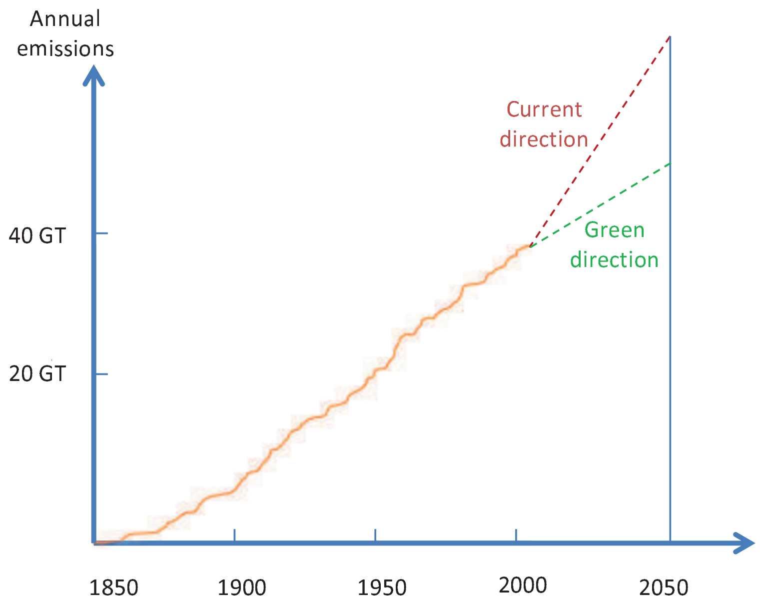

Figure 1.3: CO_2 footprint

The development of ICT and the emergence of a new economy based on knowledge and intangible have multiple complex consequences on the environment. The ICT is responsible of 0.8 GT per year. These interactions are now one emerging issue at the heart of many debates, forums and other initiatives. What is the responsibility of ICT in environmental degradation? The greenhouse gases emissions are becoming more and more important globally.

The direct impacts of ICT on the environment are numerous. They are related to both the production, the use and disposal of electrical and electronic equipments, mainly through increased consumption increased energy and raw materials as well as the proliferation of waste. Life cycle assessment (LCA) on the equipment reveal surprising figures: the manufacture of a computer of 24 kg requires 240 kg of fossil fuels, 10 times its weight. For all manufactured products, this report is one of the 10 highest ever, compared to the ratio of an automobile or refrigerator [22]. These are the phenomena of proliferation, renewal of the electrical and electronic equipment and individualization of communication practices that increase the ecological balance.

Information and communication technologies are undoubtedly part of the cause of

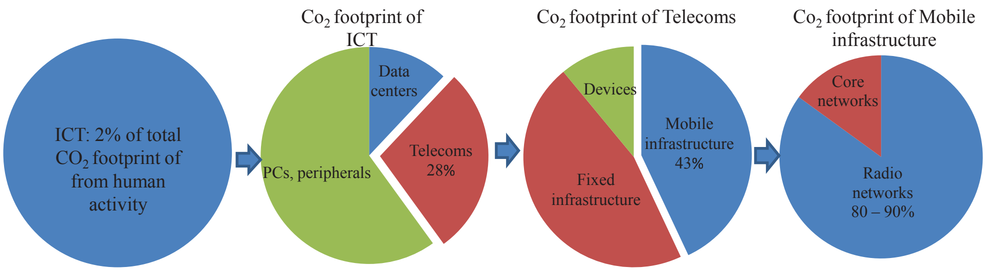

Figure 1.4: Carbon footprint of ICT

the high emission of CO_2 and the global warming as witnessed. Currently, ICT sector represents about 2% of global CO_2 emissions (around the same percentage as that of the air traffic and about one fourth as that of the road traffic) [1, 4, 23]. Out of this 2%, the total ICT emissions due to the telecommunication infrastructures and devices represents 28%. Mobile networks are responsible for 43% of CO_2 emitted by the telecommunication sector, where radio network is responsible from 80 to 90% of CO_2 footprint of mobile infrastructure. Fig. 1.4 shows the carbon emmision of different sectors of ICT. On the other hand, ICT sector is estimated to reach an emission of 2.6% of CO_2 around 2020 [4, 10]. To this effect, there is a considerable interest in the actual reduction of energy consumption in the wireless sector, especially in Europe. Orange (France), Ericsson (Sweden) and Vodafone (UK) want to significantly reduce their CO_2 emissions by a ratio of 20 to 50% by 2020 [24].

1.4 Green technologies

The main focus in green technologies is to provide new techniques to save energy consumption. Green technologies are key initiatives for future applications [25, 26, 27]. Therefore we seek in this thesis to understand what stakeholders mean by green ICT specially in wireless and wired communications. In this section we will discuss the motivation of green technologies and emerging services. We conclude with our perspective on future trends, directions and themes of research on green technologies. The main objective of green radio is to reduce CO_2 emissions by reducing energy consumption. To characterize and quantify the consumption of a communication system, it is necessary to take into account all the elements or functions requiring energy: signal processing, both on transmission and reception transducers or radio frequency (RF) heads, relays and any other intermediate signaling messages, track back and forward. A truly global approach to consumption and pollution also needs to take into account manufacturing, installation, maintenance and recycling of elements.

1.4.1 Motivations and objectives

In addition to minimize the environmental impact of ICT industry, there are a number of reasons why green technologies should be used. The main motivations for green radio are economic, ecologic, health and technical.

- On the economic front, a way to improve revenue for operators is to reduce their energy costs. On the other hand, the taxes introduced by the states on carbon emissions obligate operators to find optimal solutions for energy resource. The world economy can benefit from $ 800 billion annually [28].
- On the environment and ecology front, the energy limitation allows to conserve natural resources (water, air, gas). The restriction of the energy used involves a reduction of CO_2 emissions, enabling the ICT sector to respond to the problem of global warming . This reduction of CO_2 emissions can help other sectors to decrease their emissions of CO_2 as for example tele-medicine.
- On the health front, the experts urge caution against risks of radiation from cellular networks and mobile phones. The evidence is growing that the cellular radiation affects the health of its users [29].
- On the technical front, the renewable energy sources, use of smart grids, intelligent routing systems, and energy efficient base stations are stronger interest and set up is supported by the public and private sectors. The best use of the spectrum sharpens band spectral, allow more energy resources.

1.4.2 Green technology challenges and solutions

Environmental initiatives in the telecommunication sector today are multiple. They meet for new regulatory constraints, but also the desire to position itself as green business with consumers. Two objectives of ICT should be noted. First the increasing energy consumption of ICT must be controlled. On the other hand the shortage of natural resources for their production should be avoided. Second, it is to reduce the footprint of ICT and also help other sectors to reduce their footprint. Adding to it, the objective of stabilizing the climate. The IPCC was fixed objective to halve emissions of greenhouse gases as quickly as possible before 2050. In the telecommunication sector some challenges are cited in the literature. These challenges are kernel in a vast field that continues to evolve. To meet these challenges, one can consider various solutions. We expose thereafter, major changes that will show the green potential of radio. This list is not exhaustive, but provides some solutions proposed in the literature.

1.4.2.1 Architecture design

The main challenge is to find the best technologies and architectures to minimize energy for future network [30, 31]. As for example wireless communications, a major issue to be resolved is to define the number of base stations, the number of relays, the cell sizes and the width of band used to maximize the energy efficiency of the network. In addition, energy consumption of mobile devices, access points and femto-cells should be represented simply to avoid pushing the energy budget of consumers. Several solutions are proposed in the literature, for example:

- Virtualization is a promising solution. The virtualization in networks reduces the number of devices in the network and permits to reduce energy consumption [32].
- Cooperation between network devices is done in a manner to optimize power in the network. The use of cooperative networks in the future is a strategy where network elements are in the same class, or across domains cooperating instead of competing in the use of resources. Cooperative networks are trying to optimize overall spectrum use and reduce energy consumption. Cooperation is a logical way forward when the network elements belong to the same class. Significant gains can be obtained by the cooperation between the different networks [33]. In addition, cooperation is a simple technique used to optimize the network performance and minimize interference, for more improve energy efficiency [34].
- The traditional link between service and network is separated. There is no coordination between fixed networks and wireless networks. For example, more than

30% of mobile telephone calls are made by households users [35], generating unnecessary power consumption. Developing new architectures that allow to use the mobile network through the fixed network in the home can improve the energy efficiency. In this way, the distinction between the uplink and downlink can improve the energy efficiency. For example, the uplink using the fixed infrastructure with the help of new points access installed in homes proposed in [35] provide huge benefits.

- Using relays and femto-cells in radio networks can also be one solution. The radiation of a mobile depends on the distance from the nearest base station. Another potential network component is the use of small cells, as wireless hotspots and femto-cells (indoor). The femto-cells operate with a transmission power lower than base station [36, 37].

1.4.2.2 Metric energy

A basic task for green technologies consists in developing metrics to assess the energy efficiency of current and future networks, in order to find the best networks and architectures for less energy consumption. For example, optimization based on the metric of the life cycle for each network equipment can be used. LCA is a technique to assess energy consumption and environmental impacts associated with all the stages of a product's life [38]. Later on, academia and industry have offered several metrics for network energy efficiency. Energy metric can be defined in various perspectives. One way is to define it as the performance per unit energy consumption. The other way is to define it as the ratio of efficient output energy to total input energy. We cite in this section some metrics proposed in the literature.

- The performance metric called area power consumption is proposed in [39]. This metric is defined as the average power P_c consumed by a cell divided by the corresponding average cell A_c area measured in (W/m^2) .

$$A_1 = \frac{P_c}{A_c} \tag{1.1}$$

- The power efficiency metric is provided in [40]. This metric evaluates the efficiency of power in a cell and is defined as the number of bits per unit of energy measured in (bit/s/W).

- In [41], the performance metric relates the energy consumption in watts and the effective system throughput in bit/s and is defined as

$$A_2 = \frac{E}{R} \tag{1.2}$$

where E is the energy consumption and R is the effective system throughput.

1.4.2.3 Power effective signal

One of the challenge of networks focuses on the power reduction of the transmitted signals [42, 43]. We can consider several complementary techniques. These techniques include distributed power control, interference cancellation algorithms co-channel and distributed aperture techniques to avoid interference. Various solutions are proposed:

- Use multiple-input multiple-output antennas (MIMO) antennas that allow to reduce the emission of CO_2 by keeping the transmission rate. A profit in energy budget is 15% to 19% when using two antennas compared with the use of a single antenna [44].
- Define a new adaptive transmission power control method to the current requirements architectures [45, 46].
- Use of new materials for construction equipment telecommunications which consumes less energy [47].

1.4.2.4 Frequency management

This task focuses on the impact of the availability of frequency bands in future networks [48, 49]. The spectrum opens many new authorized bands between 300 MHz and 10 GHz. This work considers how dynamic spectrum access in Multi-band networks could be used to save energy. The access dynamic spectrum can also be used by relay links to select the radio time and frequency transmissions in the cell, to maximize the use of spectrum and minimize interference to other terminals in the network. Different solutions are proposed:

- Attaching optional green networking requirements to new spectrum license applications, or renewals could be one of the possible methods to do this. Dynamic spectrum access is developed in [48].

- Use of flexible spectrum should be exploited to reduce overall energy consumption. Cognitive radio has been studied in this direction. In [50, 51] the green radio concept is mixed with cognitive radio.

1.4.2.5 Resource allocation

This is an increasingly topic important for distributed wireless and wired networks. On the theoretical side, the recent results of energy efficiency in wireless and wired networks and the ability of Shannon's channel can provide many useful tools for developing more practical approaches to resource allocation [42, 52, 53]. The new management resource and planning techniques that optimize performance energy in the network with QoS constraints will also be well studied as techniques that mitigate the interference between the cells. The challenge is to see how the techniques of resource allocations can be used to reduce the energy. Four distinctive approaches explore this problem. The first approach comes from the perspective of the multi-user diversity gain, seeking to minimize energy consumption for all users [54]. The second approach will consider improvements to media access control (MAC) in wireless networks to minimize the energy consumption [55]. The third approach comes from the perspective of the Shannon formula analysis [56]. This work explores the trade-off between allocation of resources and energy to maximize performance. The final approach to resource allocation studies how connectivity between base stations in a cellular network can be used to reduce interference, to minimize the energy consumption and to maximize throughput.

1.5 Study context: motivation and vision

Energy consumption will be the subject of discussions of all future networks. The data on which we base our work is far from complete. The references are still scarce. We felt it necessary and important to enrich the research in this direction, in order to have a greater knowledge of the energy consumption of communication systems and better understand its evolution. We will need to design systems of next generation towards the power to deliver the services within the limited resources (energy, spectrum). Resource allocation in a communications system is a prominent issue, when one seeks to optimize its performance. Any system must indeed deal with a certain amount of physical and technological limitations and with additional constraints imposed by users. This thesis aims to study and optimize resource allocation strategies. Energy consumption will be integrated into optimization criteria. According to the paradigm proposed by Shannon, any communication channel can be divided into three blocks, namely the transmitter, the transmission channel and the receiver. From the standpoint of communication theory, the channel seen by the system includes not only the medium through which the message is propagated, the transmit filters and receiver present in all communication but also the sub-assemblies allow the message to access the medium. In this context, the work of the thesis is focused on minimizing the energy consumption at the transmitter side. Three main technologies (WiMAX, UWB, PLC) are investigated and optimized, in order to meet this challenging goal.

1.6 Conclusion

This first chapter has given us the opportunity to become familiar with the subject of the study. In this chapter, we first presented ICT sector, its impact and importance in modern society. We defined the term and stated that the ICT scope of our study is restricted to the field of ICT for telecommunications. After, we have emphasized the environmental and energy context of ICT. Then focusing on the quantification of the ICT impact different conclusions can be drawn. The rising costs of energy and the need to reduce global CO_2 emissions to protect our environment are engines of the economy and ecology emerging today. The operators of telecommunication sector take the cost of energy as a new important element in their calculation. Energy efficiency is the key for the next decade. It saves money and creates a new competitive advantage for radio and wired networks. This requires the operators to adopt green technologies. Energy efficiency will be integrated into the optimization criteria. The next chapter comprehensively discusses the fundamentals of UWB and OFDM systems. An overview of the system specifications used in this thesis is given.

Chapter 2

System specifications

2.1 Introduction

The second chapter presents the main transmission techniques exploited in this thesis. First, the principle of multi-carrier modulations and particularly the concept of OFDM is detailed. Then, an overview of the resources allocation technics is provided, which can be considered as the starting point of our studies. The second part of this chapter is dedicated to the description of UWB systems. Afterwards, the multi-band OFDM (MB-OFDM) UWB system performance is presented, followed by a discussion of the advantages and drawbacks of this technique. Finally, the considered systems in this thesis are presented. Besides the channel model adopted is also given. In addition, the energy consumption for WiMAX and PLC systems are provided.

2.2 OFDM systems

OFDM belongs to a family of transmission schemes called multi-carrier modulations, based on the idea of dividing a given high bit-rate data stream into several parallel lower bit-rate which are transmitted on separate carriers often called sub-carriers, or tones. Multi-carrier modulation permits encoding digital data on multiple carrier frequencies. The concept of frequency division multiplexing (FDM) was proposed by Doelz [57] for the first time in 1950. However, the concept of OFDM has been implemented in real systems, after various improvements, almost 40 years later as the recent developments in semiconductor and circuit miniaturization technologies have reduced the cost of the hardware and signal processing needed for multi-carrier modulation systems [58, 59]. In recent times, OFDM is considered as a leading technology for high bit-rate. Particularly, a number of standards for wired and wireless communications have chosen OFDM to improve the performance of modern communication systems. This includes LTE, WiMAX, IEEE 802.11a, terrestrial digital video broadcasting (DVB-T) and digital subscriber line (DSL) for wired and wireless communications.

2.2.1 OFDM principle

OFDM is a special form of multi-carrier modulation with densely spaced sub-carriers and overlapping spectra. The principle is based on the parallelization of the information to be transmitted. The high initial data-rate $1/T_d$ is spread across multiple frequency channels at low speed sub-carriers. If N is the number of sub-carriers used, the symbols transmitted by each of them have a duration $T_s = N \times T_d$. Then, the throughput of the multi-carrier signal is identical to that of single-carrier signal with the same spectral occupancy [60]. The signal is composed of N sub-carriers. In the frequency domain, the signal distortions introduced by the channel in this way are limited since each sub-band is narrow enough to consider the response of the channel as locally flat. The idea of dividing frequency selective wide band channels into a number of narrow band sub-channels, non-selective in frequency, is the core reason that makes the system robust against large delay spreads by maintaining the orthogonality of sub-carriers in frequency domain. In the time domain, the signal obtained is divided into symbols of duration T_s resulting from the superposition of N sinusoidal signals at different frequencies. By sufficiently increasing the number of sub-carriers, the symbol duration can be made even greater than the delay spread of the channel impulse response, which tends to minimize the effects of inter-symbol interference. In practice, an excessive increase, can not be considered due to the limitations imposed by the coherence time of the channel. Therefore, the guard interval is used. During this guard interval, no useful data is transmitted. Inserted as a cyclic prefix of each OFDM symbol, for most of the standard systems, its role is to absorb the residual inter-symbol interference, as long as its duration is chosen to be greater than or equal to the maximum spread of delays of the channel impulse response. On the other hand, one of the main reasons for its acceptance as a leading transmission technology is its ability to modulate adaptively different sub-channels. For our part, we assume that the signal is adapted to the transmission channel: the guard interval, the number of sub-carriers and the inter-carrier spacing are selected to perfectly absorb interference caused by multi-path channels and limit loss spectral efficiency generated by the guard interval.

In communication systems, the low-pass received signal $y(t)$ can be given as,

$$y(t) = \int_{-\infty}^{\infty} h(\tau)x(t-\tau)d\tau + n(t), \tag{2.1}$$

where $x(t)$ is the transmitted signal, $h(t)$ is the channel impulse response. If the transmitted signal bandwidth $[-\frac{f_x}{2}, \frac{f_x}{2}]$ is greater than the channel coherence bandwidth, frequency selectivity occurs. The channel coherence bandwidth is inversely related to the delay spread [61]. In the case of frequency selective channel, the frequency components of $x(t)$ with frequency separation exceeding the coherence bandwidth tend to have different channel gains.

2.2.2 OFDM waveform

The orthogonality of OFDM is related to the pulse shaping function. Various pulse shaping functions have been proposed in the literature [62], the rectangular function is one of them. This function can be seen as a rectangular window, with duration T_s equal to the OFDM symbol duration. In frequency domain, it can be represented by a sinc function for each sub-carrier of the generated signal. A minimum spacing between adjacent sub-carriers is required in order to attain the frequency orthogonality between the signal on N sub-carriers. For the rectangular pulse shaping, this minimum sub-carrier spacing can be expressed as

$$\triangle f = \frac{1}{T_s} \tag{2.2}$$

OFDM signal in time and frequency domains is represented in Fig. 2.1. In time domain, OFDM signal can be considered as compound function consisting of various overlapping sinusoids. In frequency domain, the OFDM signal is represented by a series of sinc functions separated by $\triangle f$. It should be noted here that in a frequency selective channel, the number of sub-carriers is very great such that the OFDM spectrum for a given sub-carrier is flat. Due to their distinct characteristics, the extraction and identification of various sub-carriers is possible everywhere in the spectrum that helps in adapting the system according to the dimension of the given spectrum. This flexibility in the spectrum management is very advantageous as it is quite possible to assign different modulation orders (i.e. different numbers of bits) and different transmit powers

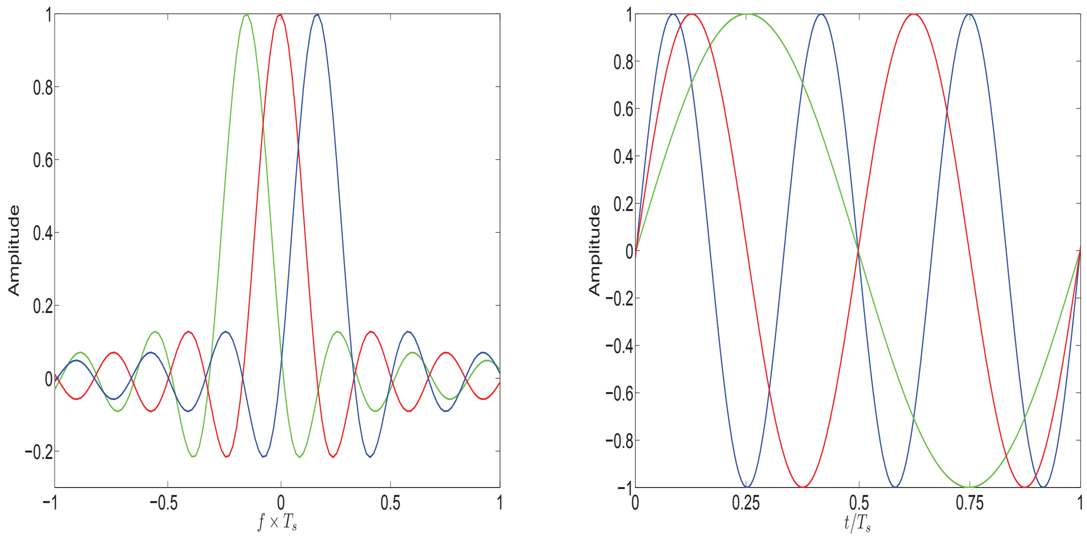

Figure 2.1: Frequency and Time domain representation of an OFDM signal

to distinct sub-carriers. The main idea is to adapt the transmitted signal according to the propagation channel under the assumption of all or partial knowledge of the channel state. It is exactly what the proposed resource allocation and optimization algorithms will exploit in order to minimize the energy consumption of the system by suitably allocating bits and energy to different sub-carriers.

2.2.3 Resource allocation in OFDM

Due to the limited availability of resources, e.g. bandwidth and energy, intelligent allocation of these resources to the users is crucial for delivering the best possible quality of service to the consumer with the least cost.

This is especially important with the high data rates envisioned for the next generation of wireless and wired standards that utilize OFDM. The problem of allocating time slots, sub-carriers, rates, and powers to the different users in an OFDM system has therefore been an area of active research [63].

In OFDM system design, bit and power allocation is considered as an essential aspect. In practical systems, the problem of resource allocation is dealt with the help of bit and power loading algorithms, which are used to distribute the total number of bits and the total available power among different sub-carriers in an optimal way to maximize the system performances.

The resource allocation can be considered as a constraint optimization problem [64] and is generally divided into two cases: margin adaptive (MA) [65] and rate adaptive (RA) [66]. The objective of MA is to achieve the minimum overall transmit power given the constraints on the users data rate and bit error rate (BER). On the other hand, the objective of RA technique is to maximize total throughput, where total transmit power is assumed to be constant. The optimization problem of RA can be formulated in the case of point multi-point under total power constraint [67]

$$\max_{P_{k,n}} \sum_{n=1}^{N} \frac{B}{N_k} \log_2(1 + \frac{P_{k,n}\alpha_{k,n}}{\frac{N_0 B}{N_k}}) \tag{2.3}$$
$$\text{subject to} \sum_{n=1}^{N} \sum_{k=1}^{K} P_{k,n} \leq P_{\max}$$

where N is the total number of sub-carriers, K the total number of users, B the total bandwidth, $P_{k,n}$ the allocated power to user k in sub-carrier n, $\alpha_{k,n}$ the channel gain of user k in sub-carriers n, N_0 the power spectrum density of additive white Gaussian noise and P_{max} the total power constraint. It was shown in [68] that in order to maximize the total capacity, each sub-carrier should be allocated to the user with the best gain on it, and the power should be allocated using the water-filling algorithm across the sub-carriers. However, no fairness among the users was considered in [68]. Thus, the users that have the best channel conditions will be assigned all the resources, which leaves many users without a chance to use the spectrum.

The margin adaptive resource allocation problem was investigated in [65], in which an iterative sub-carrier and power allocation algorithm was proposed to minimize the total transmit power given a set of fixed user data rates requirements. They applied a constraint relaxation technique, which allowed the binary integer parameter of sub-carrier assignment to take on real values, which in turn implies a time-sharing of each sub-carrier among users. The problem optimization is defined as

$$P_T = \min_{c_{k,n}} \sum_{n=1}^{N} \sum_{k=1}^{K} P_{k,n} \tag{2.4}$$
$$\text{subject to } R_k = \sum_{n=1}^{N} c_{k,n} \forall\ k \in \{1, 2, ..., k\}$$

where P_T is the total power, R_k the user k data rate, $c_{k,n}$ the number of bits per OFDM symbol of user k in sub-carrier n.

In this thesis, the bit-rate and the power is not considered for resource allocation algorithms. Our focus is on quantity of information and energy consumption. Then, the target is to minimize the energy required to transmit a given quantity of information Q. The variables are $\{Q_i\}_{i=1}^{n}$ and the optimization problem is

$$\min \sum_{i=1}^{n} (2^{\frac{Q_i}{T_i B_i}} - 1) \frac{T_i B_i N_0}{|h_i|^2} \quad \text{subject to} \begin{cases} \sum_{i=1}^{n} Q_i = Q \\ Q_i \geq 0 \end{cases} \tag{2.5}$$

where Q_i is the quantity of information allocated to sub-channel i, T_i and B_i are the transmission time and the bandwidth of sub-channel i respectively. We detail the optimization procedures for such a strategy in the next chapter.

2.3 UWB systems

2.3.1 Description of impulse radio UWB

UWB is not a new technology [69]. However, it has gained great attention recently in industry as well as in academia. The first definition for UWB signals is provided by the Defense Advanced Research Projects Agency based on the fractional bandwidth B_f of the signal which is defined as [70]

$$B_f = \frac{f_H - f_L}{f_H + f_L} \tag{2.6}$$

where f_H and f_L are respectively the higher and lower -3 dB point in the spectrum. According to the first provided definition, a signal can be classified as an UWB signal if B_f is greater than 0.25. In February 2002, the FCC approved that any signal having a -10 dB fractional bandwidth larger than 0.20, or a bandwidth greater than 500 MHz, is characterized as an UWB signal. The wide bandwidth provides many advantages over narrow-band systems [69]. In particular, UWB systems

- provide high data rates,
- have potentially small size, low complexity and low cost,
- robustness for multi-path and interference,

- allow ranging and communication at the same time.

The advantage of UWB systems compared to narrow bandwidth systems can be understood by examining the Shannon capacity formula which is expressed as [71]

$$C = B\log_2(1 + \frac{S}{N_0}) \tag{2.7}$$

where C is the maximum channel capacity in bit/s, B the channel bandwidth in Hz, and $\frac{S}{N_0}$ the signal-to-noise ratio (SNR). We notice that to improve the channel capacity, we can increase either the system bandwidth or the SNR. However, the capacity grows linearly with the bandwidth [72], but only logarithmically with the signal power. For this reason, communication engineers in general prefer to increase the system bandwidth rather than the power, to achieve higher data rates.

UWB systems can be implemented in low cost, low-power integrated circuit processes due to the baseband nature of the signal transmission. Unlike conventional radio systems, the UWB transmitter produces a very short time-domain pulse, which is able to propagate without the need of an additional radio frequency mixing stage [73]. The UWB signal spans frequencies commonly used as carrier frequencies due to its very wide-band nature. Consequently, the signal will propagate well without using additional up-conversion and down-conversion stages. Besides, single chip complementary metal-oxide semiconductor (CMOS) integration of UWB transceiver contributes directly to low cost, low power and small size devices. Because of the large bandwidth of the transmitted signal, UWB transmissions can resolve many paths, and consequently very high multi-path resolution is achieved. For instance, a Gaussian monocycle UWB transceiver experiences only a 1.5 dB fading margin in dense multi-path, which is very low compared to deep fades experienced in narrow-band systems [74]. Finally, the ultra-short duration of UWB waveforms offers the ability to provide high precision ranging and high-speed data communication. For instance, UWB radios offer timing precisions much better than the global positioning system and other radio systems [75], as well as opportunities for short-range radar applications. Modulation techniques UWB systems have historically been based on impulse radio concepts. However, since the FCC decision, different modulation techniques have been proposed for UWB applications. In this section, we describe the two main modulation techniques considered by the IEEE 802.15.3a study group for high data rate wireless personal area network (WPAN) applications: the impulse response UWB and the MB-OFDM techniques.

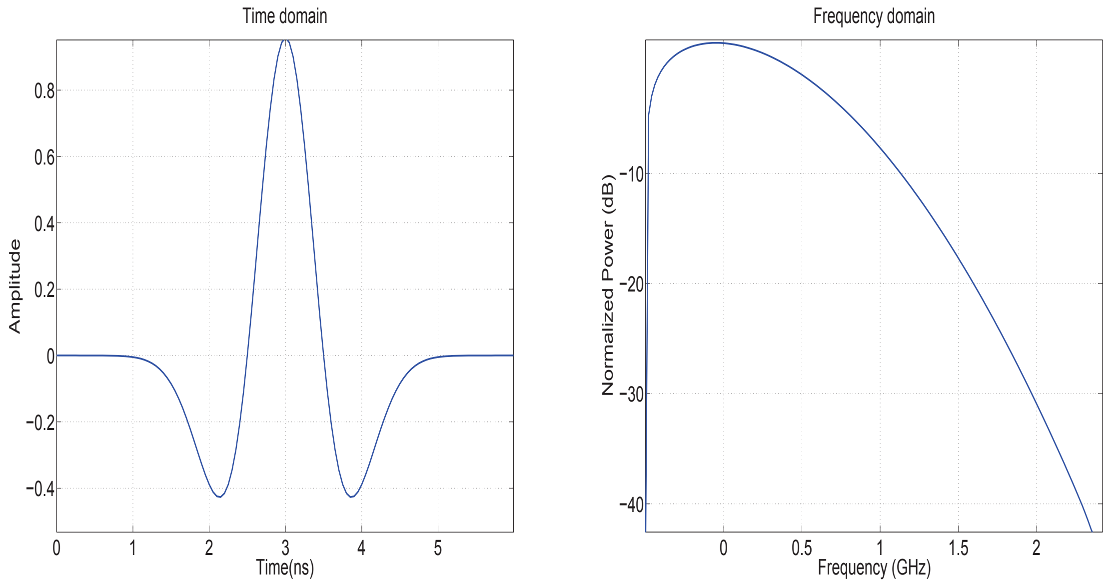

Figure 2.2: Time and Frequency domain for Second-order Gaussian mono cycle

2.3.2 Gaussian pulses

With impulse radio schemes, the information is represented by very short duration pulses so-called monocycle. Each pulse has a very wide spectrum that must adhere to the spectral mask requirements. Any waveform that satisfies the definition of UWB signal can be used. The choice of a specific waveform is driven by system design and application requirements. Many pulses are proposed for UWB communications [76]. The Gaussian pulses are frequently used since they can be easily generated [77]. Usually higher derivatives of Gaussian shape are more popular for UWB transmissions. This is mainly due to the direct current (DC) value of the Gaussian pulse. As antennas are not efficient at DC, it is preferable to use derivatives of Gaussian shape having smaller DC components [77]. One transmitted symbol is spread over many monocycles to achieve a processing gain used to combat noise and interference. The widely used pulse shapes are the derivatives of Gaussian functions [78]. Fig. 2.2 illustrates the basic Gaussian monocycle and the corresponding normalized frequency spectrum.

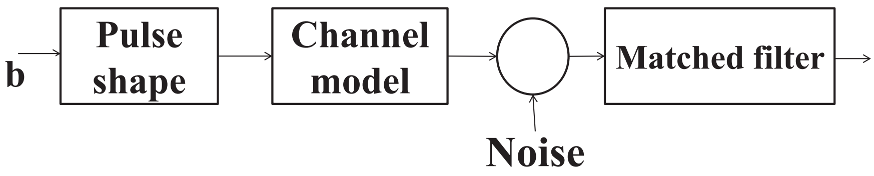

Figure 2.3: The model of the system

2.3.3 Communication model

We consider a general system model to address the single user case [79]. In our system model, we assume binary phase shift keying (BPSK) such that the signal transmitted by the desired user can be written as

$$s(t) = \sum_k b_k g(t - kT_b) \tag{2.8}$$

where $b_k = \pm 1$ denotes the information bit transmitted in the k bit, $g(t)$ is the waveform used to convey information, and T_b is the bit duration. The bit duration fulfills the relation

$$T_b = L \times (T_p + T_g) \tag{2.9}$$

where T_p is the pulse duration, T_g is the guard time and L is the pulse repetition. The guard time is inserted between frames to cope with the channel time dispersion, and eliminate the inter-symbol interference (ISI). The waveform used in transmission comprises the weighted repetition of $L \geq 1$

$$g(t) = \sum_{m=0}^{L-1} c_m g_M(t - mT) \tag{2.10}$$

where $c_m = \pm 1$ are the code word elements (chips), and T is the chip period. We incorporate the differential effects of the transmission and receive antennas into $g_M(t)$ [80]. We assume $g_M(t)$ to be the second derivative of the Gaussian pulse

$$g_M(t) = \left(1 - \pi\left(\frac{t - \frac{D}{2}}{T_0}\right)^2\right) \exp\left(-\frac{\pi}{2}\left(\frac{t - \frac{D}{2}}{T_0}\right)^2\right) \tag{2.11}$$

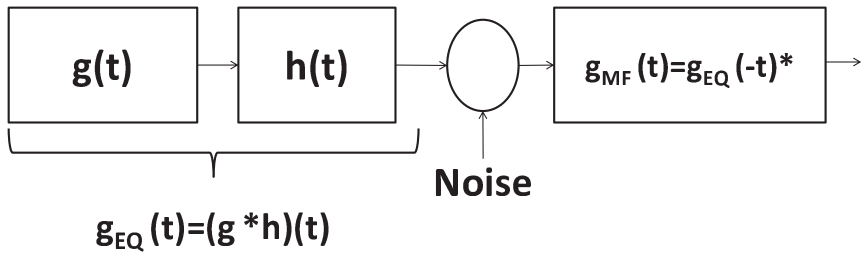

Figure 2.4: The mathematical model

where D is the monocycle pulse duration, and T_0 is the width of pulse. A guard time T_g is inserted between pulses to cope with the channel time dispersion that eliminates the inter-pulse interference. If we choose $T_b \geq T_p + T_{ch}$, we can also avoid the inter-symbol interference at the expense of a transmission-rate penalty, where T_{ch} is the maximum time dispersion introduced by the channel. At the receiver side, a bandpass front-end filter is deployed to suppress out band noise. Then, the received signal, in the single user case, can be written as

$$y(t) = \sum_k g_{EQ}(t - kT_b) + w(t) \tag{2.12}$$

where $g_{EQ}(t) = (g \star h)(t)$ is the equivalent (real) impulse response that comprises the user's waveform filter, the channel $h(t)$, and the front-end filter. Its frequency response is $G_{EQ}(f)$. The additive noise $w(t)$ is assumed to be a stationary zero mean Gaussian process. Further, we consider it to be white in the useful signal band. Let us suppose that the received signal is passed first through a filter. The optimum filter from the point of view of signal-to-noise ratio (SNR) maximization is a matched filter [61]. The frequency response of the receiving filter is $g_{MF}(f)$. The matched filter is adapted to the pulse and to the channel response. Then, it is obtained by correlating the transmit signal and the channel response [61]. The main motivation to use a matched filter is that the matched filter maximizes the SNR output and then the error probability is minimized. The model of communication system used in simulation is shown in Fig. 2.3. The mathematical model is presented in Fig. 2.4. The SNR is given by

$$\text{SNR} = \frac{E[y(t)^2]}{E[w(t)^2]} \tag{2.13}$$

where $y(t)$ represents the signal component and $w(t)$ the noise component. The received energy is equal to

$$S = E[|b(kt)|^2 |g(0)|^2] \tag{2.14}$$

$$S = M_b |g(0)|^2 \tag{2.15}$$

where $M_b \in \{-1, +1\}$

- Hence, to simplify the calculation of the SNR, it night be calculated in the frequency domain. The formula of the SNR in the frequency domain becomes

$$\text{SNR} = \frac{M_b |\int G_{\text{EQ}}(f) G^*_{\text{EQ}}(f) df|^2}{N_0/2 \int |G_{\text{EQ}}(f)|^2 df} \tag{2.16}$$

- When there is no inter-symbol interference, the output SNR obtained with the matched filter is

$$\text{SNR}b = \frac{M_b}{N_0/2} \int |G_{\text{EQ}}(f)|^2 df \tag{2.17}$$

2.3.4 Multi-band OFDM

2.3.4.1 Multi-band technique

Many companies have proposed a multi-band technique for UWB applications in order to solve common problems encountered when working on a single-band impulse radio technology. These problems include [81]

- inflexible spectrum mask because the occupied spectrum can not be easily altered since it is dictated in large part by the pulse-shaping filter,
- implementation difficulties and active circuits design giving rise to increased cost and power consumption,
- high sample rates in digital-to-analog and analog-to-digital converters,
- weakness to strong interferences,
- single-band UWB not well suited to low cost RF-CMOS implementations. A multi-band UWB signaling can be seen as a simple division of a single UWB signal into multiple sub-bands in the frequency domain. These sub-bands may be

transmitted in parallel or sequentially and may be received by separate receive paths or one single receiver. Multi-band schemes can be classified between two main approaches: pulsed multi-band and multi-band OFDM.

A pulsed multi-band approach dividing the UWB spectrum into various bands of around 500 MHz bandwidth was proposed in the literature [82]. Pulsed transmissions use a constant pulse shape to obtain the frequency-domain properties for each sub-band. The information is modulated using pulse position modulation or BPSK and transmitted on each band using narrow time-domain pulses, on the order of 2 to 5 ns [82]. Receiver detection schemes applicable to single-band UWB pulses can also be used.

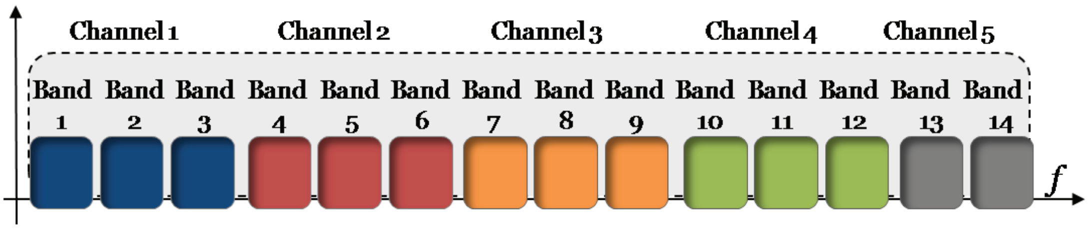

Figure 2.5: UWB spectrum bands in the MB-OFDM system

Multi-band OFDM is the primary candidate considered by UWB standardization committees. It was first proposed by Anuj Batra et al. from Texas Instruments for the IEEE 802.15.3a task group [83, 84]. This approach is based on the combination of an OFDM modulation with a multi-band technique that divides the UWB spectrum into multiple sub-bands.

The multi-band technique proposed in the WiMedia Alliance MB-OFDM scheme divides the UWB spectrum into 14 bands of 528 MHz each, as illustrated in Fig. 2.5. The first 12 bands are then grouped into four band groups consisting of three bands each. The last two bands are grouped into a fifth band group. In addition, in the ECMA-368 specification [85], a sixth band group is also defined within the spectrum of the first four, consistent with usage within worldwide regulations. Originally, most of the studies in the literature have been performed on the first band group from 3.1 to 4.8 GHz.

2.3.4.2 Impulse radio and MB-OFDM comparison

The transmitted signal in the single-band impulse radio can be easily generated in the analog domain using analog circuits. Further, when the signal bandwidth is very large, the analog circuits and mixed-signal circuits, such as the analog to digital converters in the receiver are difficult to design. Beside, these circuits consume a large amount of energy in order to process the signal at a high data rate and keep a sufficiently low noise figure. In addition, the complexity of the digital baseband is high, due to the large number of RAKE fingers that is needed to capture sufficient energy in a dense multi-path environment [86].

In the pulsed multi-band approach, the information is processed over a much smaller bandwidth which enables reducing the energy consumption and the design complexity, and improving the spectral flexibility. The multi-path energy collection can be improved by adding several RF chains, but this increases power consumption and devices cost [86].

On the other hand, the MB-OFDM approach benefits from the same multi-band advantages as the pulsed multi-band approach. The MB-OFDM system is able to capture multi-path energy efficiently with a single RF chain. Furthermore, it offers relaxed frequency-switching time requirements and increases the spectral flexibility. One particularly important issue for UWB systems is its resistance to interference [87]. The MB-OFDM system facilitates the interference avoidance based on OFDM principle. In addition, the MB-OFDM technology has been specially built by low cost CMOS processes [86], which makes it easier to integrate into a single-chip solution. One of the few drawbacks of MB-OFDM is that requires inverse discrete Fourier transform which returns the transmitter more complex. Added to this, the peak-to-average power ratio of the transmitted signal may be slightly higher than that of the pulse-based multi-band systems.

2.4 Applications

2.4.1 WiMAX

The IEEE 802.16 group was formed in 1998 to develop an air-interface standard for wireless broadband. The group's initial focus was the development of a LOS-based point-to-multipoint wireless broadband system for operation in the 10–66 GHz millimeter wave band. The original IEEE 802.16 standard, completed in December 2001 was based on a single-carrier physical (PHY) layer with a burst time division multiplexed MAC layer. The IEEE 802.16 group subsequently produced 802.16a, an amendment to the standard, to include non line-of-sight (NLOS) applications in the 2–11 GHz band, using an orthogonal frequency division multiplexing based physical layer. Additions to the MAC layer, such as support for orthogonal frequency division multiple access (OFDMA), was also included. Further revisions resulted in a new standard in 2004, called IEEE 802.16-2004, which replaced all prior versions and formed the basis for the first WiMAX solution. This WiMAX solution based on IEEE 802.16-2004 is intended to fixed applications, and we refer to this as fixed WiMAX [88]. In December 2005, the IEEE group completed and approved IEEE 802.16e-2005, an amendment to the IEEE 802.16-2004 standard that added mobility support. The IEEE 802.16e-2005 forms the basis for the mobile applications and is often referred to as mobile WiMAX. WiMAX is capable of supporting very high peak data rates. In fact, the peak PHY data rate can be as high as 74 Mbit/s [89]. The IEEE 802.16e-2005 standard offers a wide choice of optional PHY and MAC features. This section is intended to provide a high-level overview of the channel in WiMAX technology with an emphasis on the PHY layer features. The WiMAX physical layer is based on orthogonal frequency division multiplexing, which allows WiMAX to operate in NLOS conditions. WiMAX supports a variety of modulation and coding schemes and allows for the scheme to change on a burst-by-burst basis per link, depending on channel conditions. In WiMaX, the set of available sub-carriers should be divided into several groups of sub-carriers called sub-channels [90]. A sub-channel, as defined in the IEEE 802.16e-2005 standard, is a logical collection of sub-carriers. The number and exact distribution of the sub-carriers that constitute a sub-channel depend on the sub-carrier permutation mode. The permutation into sub-channels is used in the both uplink and downlink. Two methods for permutation are used in WiMAX systems [88, 90]. The first permutation uses either adjacent sub-carriers called adaptive and modulation coding (AMC). Te second permutation uses sub-carriers distributed in a pseudo-randomly in the frequency spectrum called partial usage of sub-carriers (PUSC).

The sub-channel PUSC permutation exploits the frequency diversity. With PUSC, it is possible to allocate all or part of the six sub-channel transmitters. It is also possible

SNR (dB)	Modulation	Code rate
3	BPSK	1/2
6	QPSK	1/2
8.5	QPSK	3/4
11.5	16 QAM	1/2
15	16 QAM	3/4
19	64QAM	2/3
21	64QAM	3/4

Table 2.1: MCS table

to separate the signals in the sub-frequency space, allowing greater reuse of frequencies. PUSC sub-channels are used in a context where users are highly dynamic.

The adaptive modulation and coding mode selects dynamically the coding and modulation to achieve the highest spectral efficiency for each user or each sub-channel. AMC mode depends on several channel characteristics such as the geographical distribution of users, the transmission power, the attenuation and multi-path propagation. In AMC mode, a modulation scheme with a high-order low redundancy coding is used in presence good propagation conditions, to increase the total throughput of transmission. Whereas when unfavorable conditions of propagation, the system selects a modulation scheme and a low coding rate in order to maintain the connection quality and link stability. Tab. 2.1 gives examples of modulations and codes used for different values of received SNR. The AMC permutation is used in a context where the channel is quasi static during the length of a frame transmission. AMC is an effective mechanism to maximize throughput in a time varying channel. In the context of our simulation, AMC will be taken as a model of sub-channel allocation.

2.4.1.1 Channel model

A variety of channel models have been developed to group-classify different terrain types. This information is valuable for generalized system design. The channel model used in WiMAX systems is summarized in [88]. Four typical channels for WiMAX systems (pedestrian A, pedestrian B, vehicular A, and vehicular B models) are considered. These models vary from a low-mobility pedestrian mobile users to a higher-mobility vehicular mobile users. The multi-path profile is determined by the number of multi-path taps and the power and delay of each multi-path component. Each multi-path component is modeled as independent Rayleigh fading with a potentially different power level, and the correlation in the time domain is created according to a Doppler spectrum corresponding to the specified speed. The pedestrian A is a flat-fading model corresponding to a single Rayleigh fading component with a speed of 3 km/h. The pedestrian B model corresponds to a multi-path profile with six paths of delays.

	Channel A		Channel B	
Tap Number	Delay (ns)	Relative Power (dB)	Delay (ns)	Relative Power (dB)
		Vehicular (60–120 km/h)		
1	0	0	0	−2.5
2	310	−1	300	0
3	710	−9	8900	−12.8
4	1090	−10	12900	−10
5	1730	−15	17100	−25.2
6	2510	−20	20000	−16
		Pedestrian ($\leq$ 3 km/h)		
1	0	0	0	0
2	110	−9.7	200	−0.9
3	190	−19.2	800	−4.9
4	410	−22.8	1200	−8.0
5			2300	−7.8
6			3700	−23.9

Table 2.2: ITU multi-path channel models

For the vehicular A and B models, the mobile speed is between 60 km/h to 120 km/h. The specified values of delay and the relative power associated with each of these profiles are listed in Tab. 2.2.

2.4.1.2 Energy consumption

The research field of energy efficiency in WiMAX systems is interested by researchers [91, 92, 93]. In this section we perform the energy consumption in WiMAX systems using the main algorithm for resource allocation. These results lay the first step of energy consumption in WiMAX systems and can subsequently compare these results with

Bandwidth	10 MHz
FFT size	1024
Number of sub-channels	48
Number of sub-carriers per subchannels	18
OFDM symbol duration	102 µs
Modulation	MCS table
Transmitted power	250 mW
Channel model	pedestrian A
Path-loss	$L = 128.1 + 37.6 \times \log_{10}(R)$
Shadowing	8 dB

Table 2.3: WiMAX simulated system and channel parameters

those obtained with the solution proposed in Chapter 3. Many algorithms for resource allocation are proposed in WiMAX systems [88]. The main strategy for resource allocation in WiMAX is to maximize the sum-rate under power consumption. In [94], an algorithm for resource allocation target to maximize sum-rate is proposed. For this algorithm, we perform the energy consumption of the system for different users distance. We focus on energy consumption required to transmit a certain quantity of information and not a data rate as usually. In our simulation evaluation, the energy consumption is given for one user in one cell.

The WiMAX standard was developed to suit a variety of applications and deployment scenarios. Similarly, there are multiple choices for PHY system parameters [88]. In this thesis, the chosen system parameters for the simulation are summarized in Tab. 2.3. The channel model is the pedestrian A channel with the parameters suggested in Tab. 2.2. The path-loss formula is given in Tab. 2.3. The quantity of information to be transmitted is $Q = 1$ Mbit. This limited value allows transmission over quasi static channel since the maximal transmission time is lower than the coherence time of the pedestrian channel. In that case, it is assumed that the channel transfer function is known at both transmitter and receiver sides. Fig. 2.6 shows the energy consumption for various distances between the user and the base station. The energy consumption corresponds to a certain quantity of information which depends on the user channel conditions. The user close to base station needs less energy to transmit

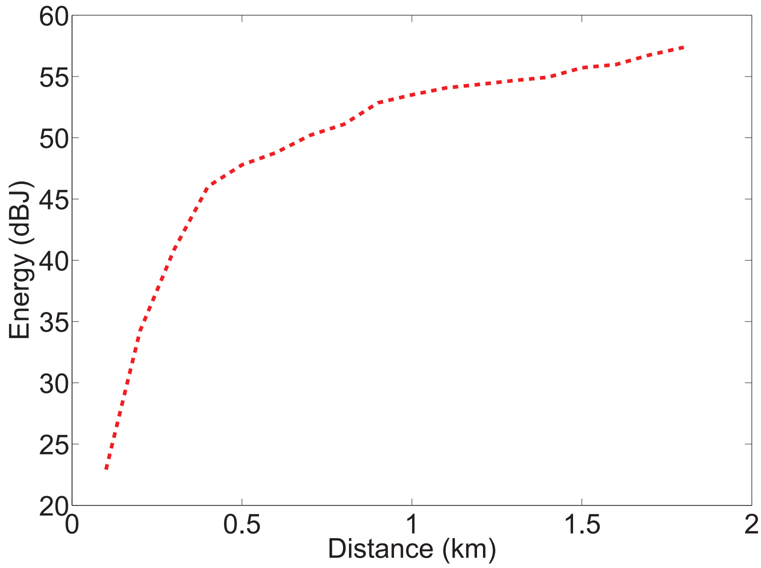

Figure 2.6: Energy consumption of conventional WiMAX systems

data as compared to a mobile that is farther away from the base station.

2.4.2 PLC

PLC technology has the advantage of the availability of the grid for robust broadband communications. In a context where the services require high-speed communications, a single access point in the home network is insufficient and the PLC has the ability to connect different networks considered segments. The global grid is divided into three sub-networks that are typically identified from corresponding voltage: high voltage (HV), medium voltage (MV) and low voltage (LV). Considering the power line as a communication system, two aspects of PLC technology can be distinguished. Part of the network consisting of exterior lines is called access network (outdoor), and the part corresponding to private facilities is called home network (indoor). The network is connected to the outdoor backbone of the telecommunications network by means of a coupler and a base station located at the foot of the MV/LV transformer. Thus, all users served by that transformer can benefit from this broadband access via the electricity network. The PLC modem can then convert the data received from the broadband connection in a form suitable for transmission over power lines. These data will be accessible by other devices (computer, TV, printer, etc) also connected to the mains via a PLC modem. It should be noted that with the rise of automation services, the network Indoor PLC is a reasonable solution for the realization of networks with a large number of terminals, not only for their applications in the industrial and commercial sector and in large buildings, but also for their applications in private households.

Industrial PLC came together in consortium to support standardization work. The consortium also allows industries to share their opinions, interests and propose their own standards. Different consortium and standards bodies define the rules for the possible use of PLC networks and devices that should be accepted by the various stakeholders such as manufacturers, Internet service providers, integrators and network operators. Some well-known consortium are listed below:

- HomePlug powerline alliance,
- Universal Power Line Association,
- Consumer Electronics Power Line Communication Alliance
- United Power Line Council,
- Continental Automated Buildings Association.

The standard focused in this thesis is the HPAV. The HomePlug AV represents the next generation of technology from the HomePlug Powerline Alliance. The HPAV alliance founded in March 2000 has now over 75 members. It works to create programs and certification requirements for reliable operation of the PLC network [95]. The alliance accelerates application for authorization to market its products and services Homeplug worldwide through mentoring programs and training on the market. The alliance has created several specifications for standards such as HomePlug 1.0 PLC, HomePlug AV (HPAV) and HomePlug broadband power line (HPAV BPL).

2.4.2.1 Power line channel

When propagating through the transmission channel, the transmitted waves are subject to various phenomena which modify their shape, their amplitude and phase. In the most general case, there may be attenuation phenomena, phase shift, reflection, diffraction or diffusion, depending on the interactions between the waves and the physical medium. PLC channel is further characterized by the high levels of interference and noise [96]. Several approaches to characterize the PLC channel, have been proposed in the literature. An interesting approach described in the PLC channel modeling multi-path is provided in [96, 97]. Other studies attempting to model the channel as two wire PLC transmission line [98] or three-wire [99] have also been published.

In addition, the modeling approach of multi-path is based on a parametric model where most of the parameters can be estimated only after the measured impulse response of the channel. The chosen approach in many projects aims at modeling the propagation channel PLC from statistical studies on a large number of measurements of the response of the channel [100].

In the process of channel modeling for PLC systems, we encounter many crucial hurdles. PLC networks differ significantly in topology, structure, and physical properties from classical media such as twisted pair cable, coaxial, and fiber-optic cables. Therefore, PLC systems have to face rather hostile characteristics [101]. PLC signals suffer from reflections caused by impedance mismatches at line discontinuities. Thus the PLC channel is characterized by a multi-path environment with frequency selective fading. Generally, the channel transfer function has a low pass characteristic. The number of branches is directly proportional to attenuation as some transmitted power is absorbed at each tap. The time domain signal is dispersed due to multi-path reflections. This dispersion is characterized by the delay spread, which is defined as the total time interval taken by signal reflections (with significant power) in arriving at the receiver from the transmitter. Inter-symbol interference that is generated by time dispersion might be compensated by using suitable equalization algorithms at the receiver.

The PLC channel could be considered as quasi static, as the frequency responses are slowly time varying but at certain times may vary suddenly due to changes in impedances at the terminal. This problem is generally caused by switching (ON/OFF) power supplies, fluorescent lamps, television sets and frequency converters etc. Then, the channel state should be regularly monitored at transmitter and receiver. The main work in this field was done by Philipps [97] and Zimmermann [96]. The frequency response of 110 m link 15-paths reference model proposed by Zimmermann is given by

$$H(f) = \sum_{p=1}^{P} g_p.\exp(-(a_0 + a_1 f^k)d_p).\exp(-j2\pi f \tau_p) \tag{2.18}$$

where τ_p is the path delay p, g_p is the weighting factor of path p, d_p is the distance in meters of the distance p and $\{a_0, a_1, k\}$. This model has been validated in the

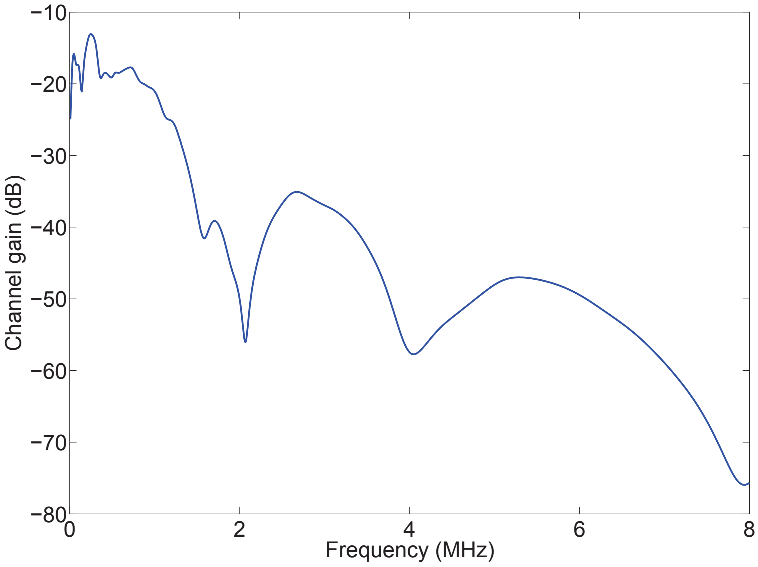

Figure 2.7: Transfer function of the reference model proposed by Zimmermann PLC channel

	attenuation parameters				
	$k = 1$		$a_0 = 0$		$a_1 = 2.510^{-9}$
	path-parameters				
p	g_p	d_p (m)	p	g_p	d_p (m)
1	0.029	90	9	0.071	411
2	0.043	102	10	−0.035	490
3	0.103	113	11	0.065	567
4	−0.058	143	12	−0.055	740
5	−0.045	148	13	0.042	960
6	−0.040	200	14	−0.059	1130
7	−0.038	260	15	0.049	1250
8	−0.038	322			

Table 2.4: Parameters of the 15-path model

frequency band from 500 kHz to 20 MHz and is valid for both indoor and outdoor environments. The inner lines are shorter, but suffer from high ramification and the number of relevant paths are generally higher. The parameters of the 15-path model are listed in Tab. 2.4. It is valid for both outdoor and indoor PLC channels. The

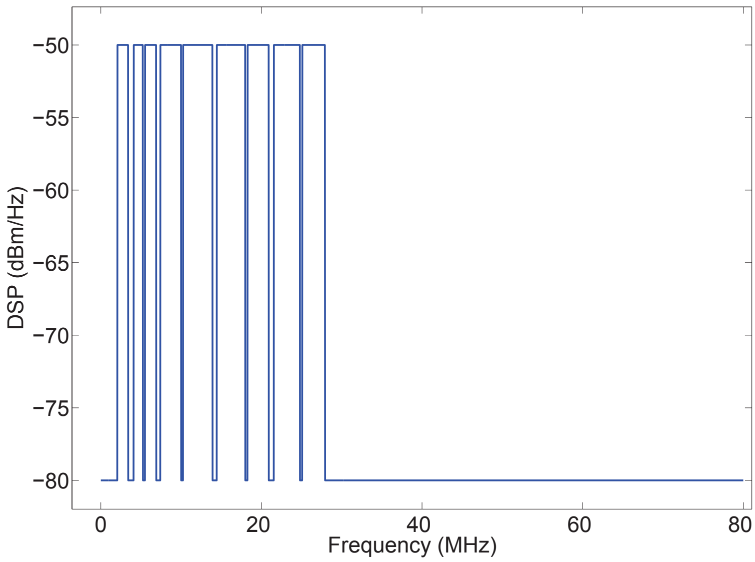

Figure 2.8: DSP mask for PLC systems

indoor lines are shorter, but they suffer from strong branching: the number of relevant paths is then usually higher while the attenuation associated with each path is smaller. Length profiles of the attenuation of power line links, i.e. neglecting the impacts of notches, as proposed in [96], and the corresponding parameters are listed in Tab. 2.4. The attenuation corresponding to the length profiles is provided in Tab. 2.5. These profiles are used to compare the performance of PLC systems at various distances.

class	g_p	a_1 (m^{-1})	a_1 (s/p)	k
100m	1	9.4 10^{-3}	4.2 10^{-7}	0.7
150m	1	1.09 10^{-2}	3.36 10^{-7}	0.7
200m	1	9.33 10^{-3}	3.24 10^{-7}	0.7
300m	1	8.4 10^{-3}	3.0 10^{-7}	1
380m	1	6.2 10^{-3}	4.0 10^{-7}	1

Table 2.5: Attenuation parameters corresponding to the length profiles

A power spectral density (PSD) mask for HPAV specification is shown in Fig. 2.8, where 4 or 5 additional sub-carriers on either side are set to zero amplitude in order to guarantee that the energy inside the licensed band will be at least 30 dB lower than the normal transmit power. A high background noise level of 110 dBm/Hz is considered for indoor PLC networks [102].

2.4.2.2 Energy consumption

Many algorithms for resource allocation have been proposed for PLC standard [103, 104]. As others technologies, the primary strategy for resource allocation in PLC is to maximize the bit-rate under power consumption. In [103], an algorithm for resource allocation target to maximize bit-rate is proposed. In this section, we present numerical evaluations of OFDM transmission in powerline communications. In particular, our attention is focused on performance of the energy consumed by a conventional PLC system. The generated signal is composed of $N = 1024$ sub-carriers transmitted in the band 0–20 MHz. The OFDM symbol duration is 57 µs including a guard interval of 5.8 µs. Perfect synchronization and channel estimation are assumed and the channel transfer function is known at both transmitter and receiver sides. The performance of simulations are computed in the case of perfect channel coding with a system noise margin equal to 0 dB. The signal is transmitted with respect to a PSD mask. Fig. 2.9 shows the energy consumption of the PLC system versus data transmission. This figure allows us to understand the relation between quantity of information and energy consumption and permits therefore to compare it with the solution proposed for energy minimization in PLC communications.

2.4.3 WiMedia

The WiMedia Alliance defines, certifies and supports enabling wireless technology for multimedia applications. WiMedia UWB technology represents the next evolution of WPAN offering end users wireless convenience for a broad range of PC and consumer electronics products. WiMedia Alliance is also focused on providing specifications for streaming video applications. WiMedia technology is an ISO-published radio standard for high-speed, UWB wireless connectivity that offers an unsurpassed combination of high data throughput rates and low energy consumption. With regulatory approval in major markets worldwide, this technology has gained broad industry momentum as evidenced by its selection for Wireless USB and high-speed Bluetooth. The standardization activity of wireless personal area networks takes place in the IEEE international standards working group 802.15. In late 2001, the IEEE established the 802.15.3a study

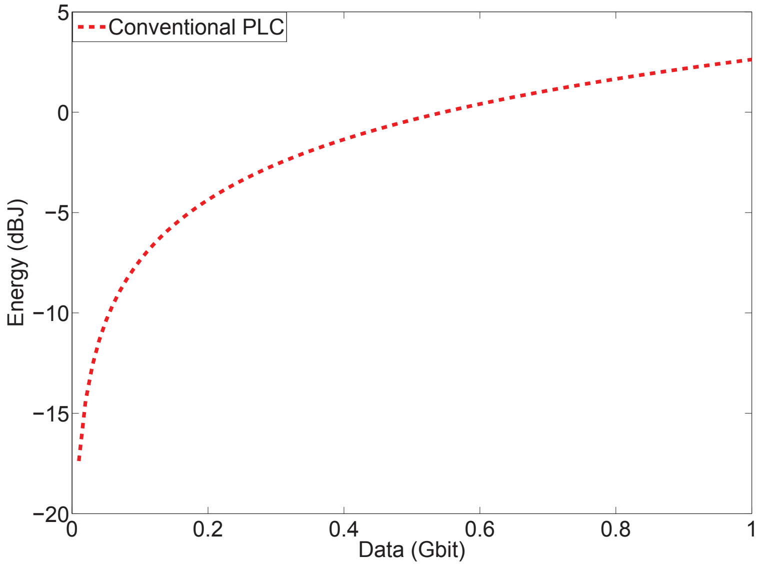

Figure 2.9: PLC energy consumption

group to define a new physical layer concept for short range high data rate WPAN applications. This was to serve the requirements of companies wishing to deploy very high data rate applications, such as video transmission, with data rates greater than 110 Mbit/s at a distance of 10 m. The technical requirements, including high data rate, short range, system scalability, low cost and low power, led to the adoption of UWB technology by the standardization group. The UWB communications support both impulse and multi-band techniques.

2.4.3.1 UWB indoor channel model

Since the late 1990s, a number of propagation studies for UWB signals have been carried out and led to some notable publications by Cassioli, Win, Molisch, Scholtz, and Foerster [105, 106, 107, 108]. In UWB channels, each multi-path component can lead to delay dispersion. In an indoor environment due to the very fine resolution of UWB waveforms, different objects or walls in a room could contribute to different clusters of multi-path components. The IEEE 802.15.3a committee adopted a new UWB channel model for the evaluation of UWB physical layer proposals [109]. This model is based on the well known Saleh-Valenzuela model for indoor channels [110], but with modified fading statistics to fit the properties of measured UWB channels. Multi-path channel characteristics are summarized in Tab. 2.6. A log normal distribution is

	CM1	CM2	CM3	CM4
Mean excess delay(ns)	5.05	10.38	14.18	
Mean excess delay(ns)	5.28	8.03	14.28	25
Distance(m)	< 4	< 4	4–10	4–10
LOS/NLOS	LOS	NLOS	NLOS	NLOS

Table 2.6: UWB channel characteristics

used for the multi-path gain magnitude. In addition, independent fading is assumed for each cluster and each ray within the cluster. The impulse response of the multi-path model is given by

$$h_i(t) = G_i \sum_{z=0}^{z_i} \sum_{p=0}^{p_i} \alpha_i(z,p) \triangle (t - T_i(z) - \tau_i(z,p)) \tag{2.19}$$

where G_i is the log normal shadowing of channel realization i, T_i is the delay of cluster z, $\alpha_i(z,p)$ and $\tau_i(z,p)$ represent the gain and the delay of multi-path p whiten cluster z. The cluster and the path arrival times can be modeled as Poisson random variables. The path amplitude follows a log-normal channel models (CM1 to CM4) and are defined for the UWB system modeling, each with arrival rates and decay factors chosen to match different usage scenarios and to fit line-of-slight and non-line-of-slight cases. An example of realization in the time and frequency domain of the UWB channels (CM1,CM2, CM3, CM4) are presented in Fig. 2.10.

2.5 Conclusion

In this chapter, we have started by presenting the principles of the main transmission techniques that we are dealing with in this thesis. Since OFDM and UWB seem to be the most promising candidates for high data rate for wireless and wired applications, due to their numerous advantages and the wide support by the standardization and industrial groups, one part of this thesis will focus on OFDM systems. The principle of multi-carrier modulation was shortly presented followed by the description of the OFDM signal. Furthermore, the fundamentals of multi-carrier resource allocation were discussed.

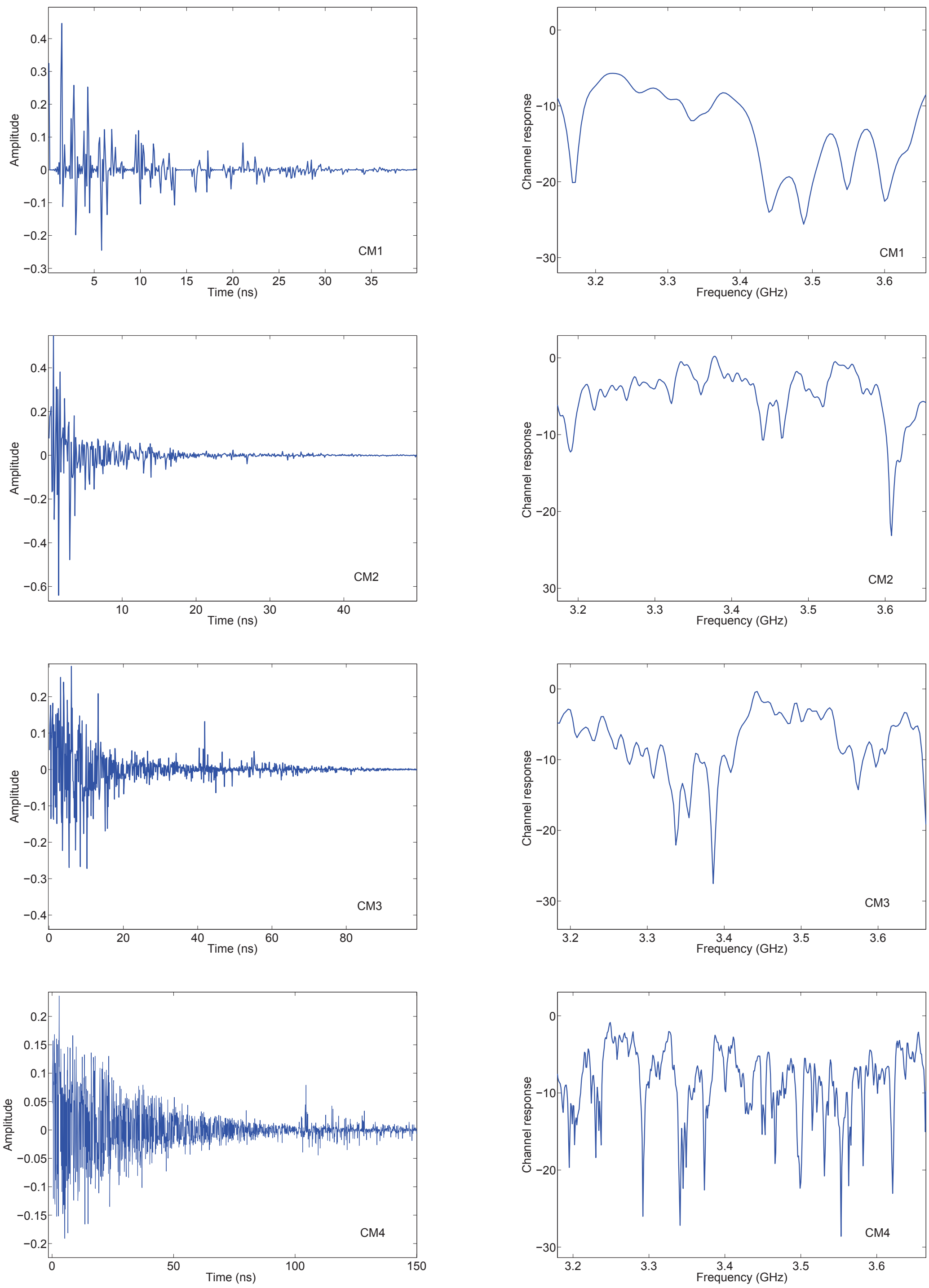

Figure 2.10: Example of UWB channel realizations for models CM1, CM2, CM3, CM4, in time and frequency domains

In addition, we have presented a general overview on UWB technology which makes the reader familiar with the UWB environment. In brief, UWB has emerged as an exciting technology for wireless communications since 2002 when the FCC allocated a 7.5 GHz spectrum for unlicensed use of UWB devices. As described, UWB holds enormous potential for wireless applications, which can used to minimize energy. Besides, we have seen that there are two main modulation schemes considered for UWB communications: the impulse UWB and MB-OFDM techniques.

Finally, an overview of energy consumption in WiMAX and PLC systems has been provided. Simulation results from rate maximization algorithms were also presented. The resource allocation strategies considered in this chapter did not take into account the energy consumption. The next chapter will present the energy minimization problem for single and multi-carrier systems. Different modifications will be proposed in the following chapter to improve the energy efficiency of WiMAX and PLC systems.

Chapter 3

UWT approach: Application to resource allocation of OFDM systems

3.1 Introduction

After having presented the system specifications in the previous chapter, here we discuss the energy minimization strategies under quantity of information constraint for single and multi-carrier systems. Our analysis is independent to the technologies constraint. Our goal is to define the asymptotic limit for communication systems. This chapter deals with the fundamental energy optimization of a general class with single and parallel channels. We show that it is possible to significantly reduce the transmitted energy by focusing only on the physical layer point-to-point. Here, it is not the power transmitted with bit-rate constraint which is minimized, but the corresponding energy consumption to transmit a quantity of information. The bandwidth was relaxed in the case of UWB. We propose to relax the time constraint and define energy efficiency as a characteristic of the link.

In the previous chapter, the OFDM system and the general principle of resource allocation for multi-carrier modulations have been described. In this chapter, we discuss the strategy of energy minimization for OFDM systems. We propose here different allocation strategies for OFDM based on a new approach to minimize energy. The goal is to optimize the energy consumption of OFDM systems. A general overview of energy consumption is first studied and the different optimization strategies, namely, energy minimization are described. The objective is to propose a new algorithms for resource allocation to reduce the energy consumption that corresponds to the constraint of the quantity of information transmitted in WiMAX and PLC networks.

In the first phase, we survey key results from information theory. Therefore, we realize an asymptotic study for energy consumption in single and multi-carrier systems. The results of study permit to define the limit of energy consumption for data transmission and lead to propose a new approach of communication systems. This approach provides a basis for the development of resource allocation optimization. Especially those based on the energy efficiency metric criterion is the first original contribution of this dissertation.

In the second phase, we focus on resource allocation for parallel channels. The solutions developed aim at proposing distribution of bits and energy in communication systems. Three cases of resource allocation are studied in order to obtain better energy efficiency for multi-carrier systems in comparison to existing solutions. The new solutions are the second original contribution of this dissertation.

The proposed resource allocation approach can be used for all parallel channel models. The results are shown only for OFDM schemes on both systems PLC and WiMAX. Besides, the performances of the proposed allocation algorithms are discussed and the simulation results obtained with the OFDM scheme of the proposed system are compared to the results obtained with the OFDM scheme presented in the previous chapter. The different optimization results presented in this chapter show that a significant improvement for energy consumption will be obtained with the proposed solutions.

3.2 Energy versus quantity of information

Before defining the energy efficiency and describing new algorithms for resource allocation, it is necessary to perform an asymptotic study to define the energy consumption required to transmit an amount of quantity of information. Thus we calculate the energy limit or the minimum energy for transmitting a given amount of information. The first study is realized for single carrier communication, followed thereafter by the asymptotic calculation in the case of multi-carrier systems.

3.2.1 Fundamental of information theory

From Shannon limit [71], the capacity in bits per two dimensions (bit/s/Hz) of additive white Gaussian noise channel is

$$C = \log_2\left(1 + \frac{P}{BN_0}\right) \tag{3.1}$$

This formula gives the capacity of transmission, where P (W) is the transmitted power, B (Hz) is the channel bandwidth and N_0 (W/Hz) is the noise spectral density. The transmission of Q bits in a bandwidth B requires a communication duration time T (second) such that

$$Q = C \times B \times T \tag{3.2}$$

The relation between the power P and energy J is

$$P = \frac{J}{T} \tag{3.3}$$

From Shannon capacity, (3.2) and (3.3), the quantity of information Q can be written as

$$Q = TB\log_2\left(1 + \frac{J}{TBN_0}\right) \tag{3.4}$$

where J (Joule) is the total energy required to send Q bits and

$$J = \left(2^{\frac{Q}{TB}} - 1\right)TBN_0 \tag{3.5}$$

3.2.2 Lower bound of energy

To save energy, transceivers can be designed to maximize information per unit energy. In [56], the required minimum energy is reached when the number of degrees of freedom is unlimited. The number of degrees of freedom is represented by one frequency-time element from the formula (3.5) [111]. With infinite time of transmission or infinite bandwidth, for a given Q, the number of degrees of freedom tends to infinity and the required energy can then be minimized. The asymptotic limit for the energy required to transmit one bit is calculated in [56] for wide band communication. With delay tolerant applications and networks, the constraint on the time of transmission can be relaxed [112, 113]. The trade-off between time and energy consumption in (3.5)

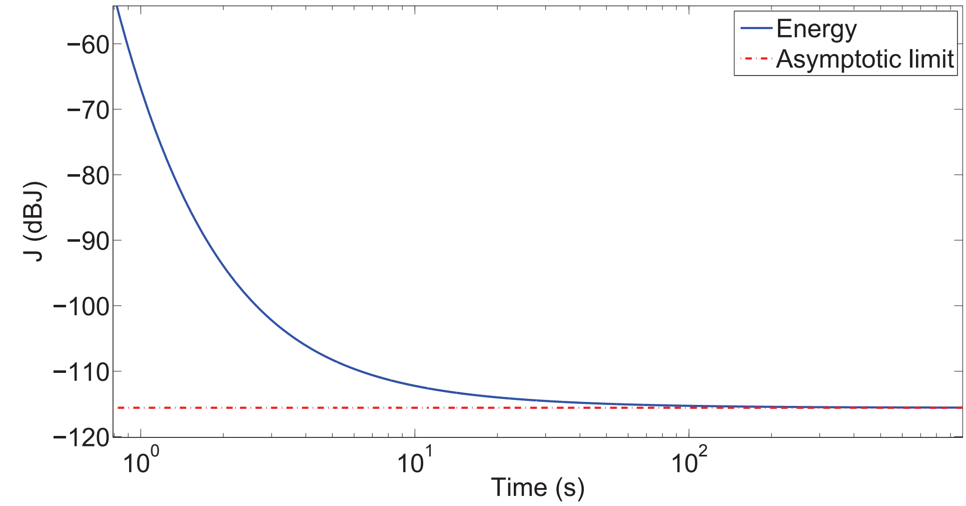

Figure 3.1: Relationship between energy and time, $Q = 1$ Gbit, $B = 50$ MHz.

is shown in Fig. 3.1. In this example $Q = 1$ Gbit, $B = 50$ MHz and N_0 is the noise spectral density. We show that the energy decreases as the time increases. For low energy consumption, it is then necessary to transmit a set of data over a long period of time which defines the new approach called UWT [114]. The solution to the problem of minimization of the transmitted energy leads to the use of an infinite time of transmission. By definition, the quantity of information and energy achieved with UWT is bounded by

$$\lim_{T\to\infty} Q = \frac{J}{N_0}\log_2 e \tag{3.6}$$

and

$$\lim_{T\to\infty} J = QN_0\log_e 2 \tag{3.7}$$

With UWT approximation, the relation between J and Q is linear and the transmission time T tends to infinity. The same results can be presented in UWB regime where the bandwidth with UWB corresponds to the time with UWT. The ratio J/Q obtained using (3.7) is lower than that obtained with (3.5) leading to energetically efficient UWT communications. Note that (3.6) and (3.7) are related to the minimum required SNR per bit, for reliable communications, through the relationship

$$\frac{E_b}{N_0} = \log_e 2 \tag{3.8}$$

where $E_b = \frac{J}{Q}$.

3.3 UWT approach and energy efficiency

The minimal achievable needed energy can be obtained in UWT regime. With UWT, minimization of energy consumption leads to infinite time of transmission. To overcome this drawback, it becomes interesting to study and develop resource allocation schemes that ensure reliable communications with a given energy constraint near to the asymptotic energy limit but with a finite bandwidth and time of transmission. To analytically formulate the objective, in this thesis we introduce a novel metric for the energy efficiency. It is defined as the ratio between the asymptotic energy limit and the energy required to transmit an amount of bits with limited time and bandwidth resources. The minimization of the transmitted energy to send an amount of information bits has been studied for a Gaussian channel in non-asymptotic regime in [115] and the result has been extended to wireless networks in [116]. To characterize the energy consumption of communication systems, we define a new performance measure β, called hereafter the energy efficiency, as follows.

Definition 2 *The energy efficiency β is the ratio between the asymptotic limit energy of a system and the energy consumed by this system.*

With this definition, β verifies $0 < \beta \leq 1$. A communication system is then efficient if β is close to 1 and $\beta = 1$ is reached for infinite time. Note that, in practice, β is different from 0 since no communication system can consume infinite energy in finite time. With Definition 2 and for a given energy efficiency β, the energy $J(\beta)$ needed to transmit Q bits is

$$J(\beta) = \frac{1}{\beta} N_0 Q \log_e 2 \tag{3.9}$$

from (3.4) and (3.9), it yields

$$Q = TB \log_2 \left(1 + \frac{Q \log_e 2}{\beta TB} \right) \tag{3.10}$$

On the other hand, the spectral efficiency in bit/s/Hz is the key measure of channel capacity in communication systems [117]. Let c be the spectral efficiency in bit per two dimensions

$$c = \frac{Q}{TB} \tag{3.11}$$

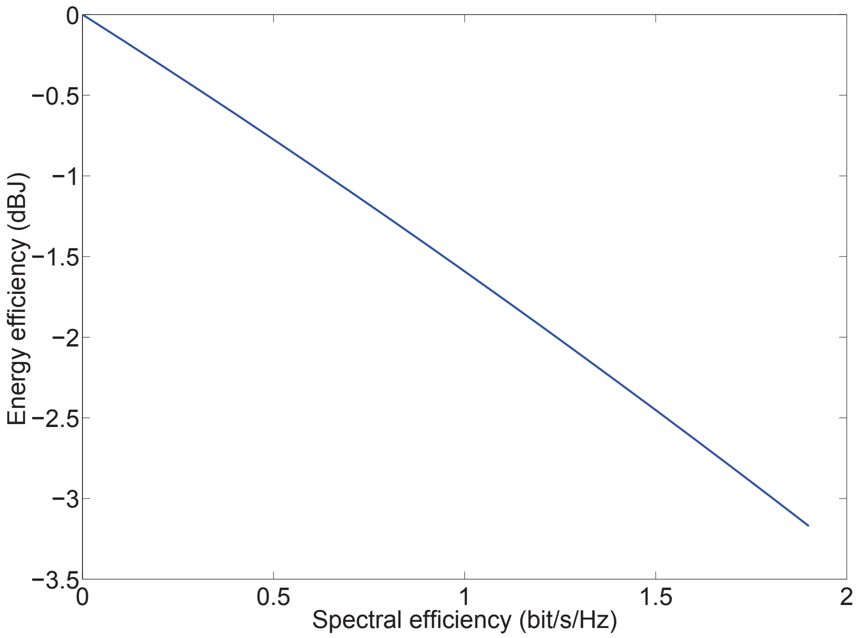

Figure 3.2: Relationship between spectral efficiency and energy efficiency.

Using (3.10) and (3.11), the spectral efficiency and the energy efficiency are related as follows

$$\frac{2^c - 1}{c} = \frac{\log_e 2}{\beta} \tag{3.12}$$

The relationship between energy efficiency and spectral efficiency is a bijective function shown in Fig. 3.2. The optimization of a communication system under energy efficiency constraint is then similar to the optimization of the system under spectral efficiency constraint. For example, the energy efficiency required to transmit a quantity of information with spectral efficiency $c = 1$ bit/s/Hz is $\beta = -1.6$ dB. This energy efficiency is independent of time. On the other hand, for a given capacity, the energy needed to transmit a quantity of information is related to the amount of information.

3.4 Resource allocation of parallel and quasi-static channels

In any communication system, the allocated frequencies and the transmit energy are the keys of any resource allocation. The systems are assigned limited frequency band, which explains why the frequency allocation is a critical issue that should be considered carefully in order to respect the regulations. Furthermore, the allocated energy is a constraint imposed by the regulation such as medical and industry regulations. Here, we focus on resource allocation of parallel and quasi static channels. Several techniques based on parallel transmission as OFDM and MIMO systems are considered.

3.4.1 Lower bound of energy

The capacity of N parallel and independent channels is the sum capacity of these channels given by

$$C = \sum_{i=1}^{N} \log_2 \left(1 + \frac{J_i}{B_i T_i N_0} |h_i|^2\right) \tag{3.13}$$

where $|h_i|^2$ is the gain of sub-channel i, and J_i is the energy allocated to this sub-channel. The transmission time of the channel i is T_i and B_i is the corresponding bandwidth of the channel. Using the notation of the previous section, the formula of quantity of information of multi-carrier systems is

$$Q = \sum_{i=1}^{N} T_i B_i \log_2 \left(1 + \frac{J_i}{B_i T_i N_0} |h_i|^2\right) \tag{3.14}$$

To transmit the quantity of information Q, the total energy used is

$$J = \sum_{i=1}^{n} (2^{\frac{Q_i}{T_i B_i}} - 1) \frac{T_i B_i N_0}{|h_i|^2} \tag{3.15}$$

where Q_i is the quantity of information allocated to sub-channel i and $\sum_{i=1}^{N} Q_i = Q$. With UWT approach, the asymptotic limit is given by an infinite time of transmission or infinite bandwidth. The energy minimization leads to infinite time as described in the previous section. The energy achieved with UWT is then

$$\lim_{T \to \infty} J = N_0 \log 2 \sum_{i=1}^{n} \frac{Q_i}{|h_i|^2} \tag{3.16}$$

The resource allocation problem with UWT returns to define the quantity of information allocated to each channel. The lower bound energy consumption is then

$$J^{\infty} = \min_{\sum\limits_{i=1}^{n} Q_i = Q} \lim_{T \to \infty} J \tag{3.17}$$

A simple solution in UWT context is to transmit all the data on the best channel. The best channel is the channel that provides the best SNR. The lower bound of transmitted energy consumption with parallel channels is then

$$J^{\infty} = \frac{Q N_0 \log 2}{\max\limits_i |h_i|^2} \tag{3.18}$$

and is reached with an infinite time of transmission.

Proof

Let $j = \arg\max\limits_i |h_i|^2$, the total energy is the sum of the energies, for an infinite time of transmission,

$$\sum_i J_i = \sum_{i=1}^{N} \frac{Q_i \log 2}{|h_i|^2} \tag{3.19}$$

$$\sum_i J_i = \frac{Q \log 2}{|h_j|^2} + \sum_{i \neq j} (\frac{1}{|h_i|^2} - \frac{1}{|h_j|^2}) Q_i \log 2 \geq \frac{Q \log 2}{|h_j|^2} \tag{3.20}$$

Then, the total energy is minimal for $Q_i = 0$, $\forall i \neq j$. This limit defines a bounded set of energy like channel capacity which is an upper bound rate. We note that the limit energy of N channels is not the sum of the minimum energy of each channel, whereas the capacity of N independent channels is the sum of the capacities of each channel.

3.4.2 Water-filling solution

In this section to simplify the approach, we choose B and T independent of i which is the case with OFDM systems, where the transmission time T is the same for all sub-channels and B is the bandwidth of each sub-channel. To transmit the quantity of information Q, the total energy used is

$$J = \sum_{i=1}^{n} (2^{\frac{Q_i}{TB}} - 1) \frac{T B N_0}{|h_i|^2} \tag{3.21}$$

The problem turns out to minimize the total energy J under constraints T, B and $\sum_{i=1}^{n} Q_i = Q$. One approach to solve this minimization problem is based on a water-filling optimization. The water-filling scheme greatly simplifies the transmitter and receiver design, and it has been the subject of a considerable number of studies. In this dissertation, the optimization problem can be equivalently expressed as

$$\min \sum_{i=1}^{n} (2^{\frac{Q_i}{TB}} - 1) \frac{TBN_0}{|h_i|^2} \tag{3.22}$$
$$\text{subject to} \begin{cases} \sum\limits_{i=1}^{n} Q_i = Q \\ Q_i \geq \; 0 \end{cases} .$$

The solution is obtained using the Lagrangian relaxation and Karush-Kuhn-Tucker (KKT) conditions [118]. The Lagrangian of the optimization problem is

$$\begin{aligned} L(\{Q_j\}_{j=1}^{n}, \lambda, \{\mu_i\}_{i=1}^{k}) = & \sum_{i=1}^{n} (2^{\frac{Q_i}{TB}} - 1) \frac{TBN_0}{|h_i|^2} \\ & + \lambda \left(Q - \sum_{i=1}^{n} Q_i \right) - \sum_{i=1}^{n} \mu_i Q_i \end{aligned} \tag{3.23}$$

and the KKT conditions associated with the constrained minimization problem, given in (3.22) are [118]

$$-Q_i \leq 0 \,, \; \forall i \in [1, n] \tag{3.24}$$
$$Q - \sum_{i=1}^{n} Q_i = 0 \tag{3.25}$$
$$\mu_i \geq 0 \,, \; \forall i \in [1, n] \tag{3.26}$$
$$\mu_i Q_i = 0 \,, \; \forall i \in [1, n] \tag{3.27}$$
$$\frac{\partial}{\partial Q_i} J\left(\{Q_i\}_{i=1}^{n}\right) - \lambda - \mu_i = 0 \,, \; \forall i \in [1, n] \tag{3.28}$$

The optimal solution that solves (3.24)–(3.28) is then

$$\begin{cases} \text{if} \quad \mu_i = 0 \quad \Rightarrow \quad \lambda = \frac{\partial}{\partial Q_i} J\Big(\{Q_i\}_{i=1}^{n}\Big) \\ \text{if} \quad \mu_i \neq 0 \quad \Rightarrow \quad Q_j^*(\lambda) = 0 \end{cases} \tag{3.29}$$

(3.29) and (3.22) can be solved using the set $\mathcal{I}$ such that

$$i \in \mathcal{I} \quad \text{iff} \quad \mu_i = 0 \tag{3.30}$$

The Lagrangian multiplier λ is identified using the equality constraint and the optimal quantity of information allocated to sub-channel $i \in \mathcal{I}$ is then

$$Q_i^* = TB\left(\frac{\frac{Q}{TB} - \sum_{j\in\mathcal{I}} \log_2 \frac{|h_j|^2}{N_0 \log 2}}{|\mathcal{I}|} + \log_2 \frac{|h_i|^2}{N_0 \log 2}\right) \tag{3.31}$$

where $|\mathcal{I}|$ is the size of $\mathcal{I}$, and the quantity of information allocated to sub-channel $i \notin \mathcal{I}$ is

$$Q_i^* = 0 \tag{3.32}$$

The solution $\{Q_i^*\}_{i=1}^n$ minimizes the total energy, given in (3.21), used to transmit Q bits over n sub-channels and verifies

$$\sum_{i=1}^{n} Q_i^* = Q \tag{3.33}$$

This solution solves (3.22) with a given communication time T, bandwidth B and number N of parallel independent channels.

3.4.3 Energy efficiency optimization

3.4.3.1 Minimization of maximum time of communication

As indicated previously the energy efficiency β is used to characterize the transmitted energy of communication systems. The goal is hereafter then to find the bit and the associated energy distributions among parallel channels for a given energy efficiency. The resource allocation objective is then to find the combination of $\{Q_i, T_i\}_{i=1}^n$ that satisfies the energy constraint $\frac{J^\infty}{\beta}$. In that case and from (3.9), the energy used is

$$\frac{J^\infty}{\beta} = \frac{1}{\beta}\frac{QN_0 \log_e 2}{\max_i |h_i|^2} \tag{3.34}$$

The optimization problem can be written as follows

$$\min \max_i \; T_i \quad \text{subject to} \begin{cases} \sum_{i=1}^{n} Q_i = Q \\ \sum_{i=1}^{n} J_i = \frac{J^\infty}{\beta} \\ Q_i \geq \; 0, \; J_i \geq \; 0 \end{cases} \tag{3.35}$$

In this section, the problem is solved in the case of uniform spectral efficiency: all the channels are exploited with the same spectral efficiency and with the same channel bandwidth, $\forall i \in [1; n]$, $B_i = B$. The spectral efficiency c is

$$c = \frac{Q_i}{BT_i} \tag{3.36}$$

As the infinite norm is not differentiable, the p-norm is used. The optimization problem becomes

$$\begin{aligned} \min \lim_{p\to\infty} \left(\sum_{i=1}^{k} T_i^p\right)^{\frac{1}{p}} &= \lim_{p\to\infty} \min \left(\sum_{i=1}^{k} T_i^p\right)^{\frac{1}{p}} \\ &= \lim_{p\to\infty} \min \sum_{i=1}^{n} T_i^p \end{aligned} \tag{3.37}$$

Note that with (3.4) and (3.5), if $Q_i \geq 0$ then $J_i \geq 0$ and the converse is true. One constraint can then be removed. The Lagrangian of problem (3.35) is

$$\begin{aligned} L = &\sum_{i=1}^{n} T_i^p + \lambda \left(\frac{J^\infty}{\beta} - \sum_{i=1}^{n} J_i\right) \\ &+ \mu \left(Q - \sum_{i=1}^{n} Q_i\right) - \sum_{i=1}^{n} \nu_i J_i \end{aligned} \tag{3.38}$$

There is no simple form for this Lagrangian. We then first solve the Lagrangian with only energetic constraint and secondly we introduce the data constraint to solve the problem. The Lagrangian of the sub-problem is

$$\begin{aligned} L(\{J_j\}_{j=1}^n, \lambda, \{\nu_i\}_{i=1}^k) = &\sum_{i=1}^{n} \left(J_i \frac{|h_i|^2}{BN_0(2^c - 1)}\right)^p + \\ &\lambda \left(\frac{Q}{B} \frac{N_0 \log 2}{\max_i |h_i|^2} - \sum_{i=1}^{n} J_i\right) - \sum_{i=1}^{n} \nu_i J_i \end{aligned} \tag{3.39}$$

and the KKT conditions are

$$-J_i \leq \ 0, \forall i \in [1, n] \tag{3.40}$$

$$J - \sum_{i=1}^{n} J_i = 0 \tag{3.41}$$

$$\nu_i \geq \ 0, \forall i \in [1, n] \tag{3.42}$$

$$\nu_i J_i = 0, \forall i \in [1, n] \tag{3.43}$$

$$\frac{\partial}{\partial J_i} L\left(\{J_i\}_{i=1}^n\right) - \lambda - \nu_i = 0, \forall i \in [1, n] \tag{3.44}$$

The optimal solution that solves (3.40)–(3.44) is then

$$\begin{cases} \text{if} \quad \nu_i = 0 \quad \Rightarrow \quad J_i^{p-1}(\lambda) = \left(\frac{\lambda B N_0 (2^c - 1)}{p|h_i|^2}\right)^p \\ \text{if} \quad \nu_i \neq 0 \quad \Rightarrow \quad J_i(\lambda) = 0 \end{cases} \tag{3.45}$$

Let $\mathcal{I}$ such that $\forall i \in \mathcal{I}$, $\mu_i = 0$. Using (3.45) and the energetic constraint, it yields for all j in $\mathcal{I}$

$$J_j = \frac{\frac{J^\infty}{\beta}}{\sum\limits_{i \in \mathcal{I}} \left(\frac{|h_j|^2}{|h_i|^2}\right)^{\frac{p}{p-1}}} \tag{3.46}$$

and

$$J_j^* = \lim_{p \to \infty} J_j = \frac{J^\infty}{\beta} \frac{|h_j|^{-2}}{\sum\limits_{i \in \mathcal{I}} |h_i|^{-2}} \tag{3.47}$$

With (3.15), the minimum time is

$$T_j^* = \frac{\frac{1}{\beta} \frac{Q \log 2}{\max\limits_i |h_i|^2}}{B(2^c - 1) \sum\limits_{i \in \mathcal{I}} |h_i|^{-2}} \tag{3.48}$$

We observe that T_j^* is independent of j, $\forall j \in \mathcal{I}$, $T_j^* = T^*$. Therefore, this solution leads to uniform distribution among a subset of channels. It is important to note that this solution differs from the water-filling solution obtained with transmission time constraint. The last unknown parameter for allocation is the spectral efficiency c. Thus, the problem to minimize the time T returns to solve

$$\frac{c}{(2^c - 1)} = \frac{\beta}{|\mathcal{I}| \ \log 2} \sum_{i \in \mathcal{I}} \frac{\max\limits_i |h_j|^2}{|h_i|^2} \tag{3.49}$$

where the unknown parameter is c. Let

$$w = \frac{\beta}{|\mathcal{I}| \ \log 2} \sum_{i \in \mathcal{I}} \frac{\max\limits_i |h_j|^2}{|h_i|^2} \tag{3.50}$$

Then, we can write (3.49) as follows

$$w 2^c - c - w = 0 \tag{3.51}$$

The minimum time may be obtained by an iterative algorithm to search the set $\mathcal{I}$ of the active channels which minimizes T. The quantity of information for each channel is then

$$Q_j^* = \frac{\frac{1}{\beta}\frac{Q\log 2}{\max_i |h_i|^2}}{(2^c-1)\sum_{i\in\mathcal{I}} |h_i|^{-2}}\left(1+\frac{(2^c-1)J^\infty}{\frac{Q\log 2}{\max_i |h_i|^2}}\right) \tag{3.52}$$

3.4.3.2 Channel occupancy cumulative time optimization

With some communication systems, it may be attractive not to minimize the communication time, but the channel occupancy cumulative time that we will named cumulative time. The advantage is to release as soon as possible channels for other communications. The solutions that minimize the cumulative time target to maximize the availability of these channels. For instance, with a given efficiency, the problem is defined as

$$\min \sum_i T_i \quad \text{subject to} \begin{cases} \sum_{i=1}^n Q_i = Q \\ \sum_{i=1}^n J_i = \frac{J^\infty}{\beta} \\ Q_i \geq\ 0,\ J_i \geq\ 0 \end{cases} \tag{3.53}$$

The solution is stated in a simple analytical form if the channels have the same bandwidth. Minimization of the cumulative time channel occupancy, where the bandwidth B is fixed for the quantity of information Q under the constraint of energy efficiency leads to transmit all the information on the best channel. Intuitively, we understand that giving a certain amount of information to a channel that is not maximal requires more time or energy than if this quantity information is assigned to the best channel.

Proof

Let us suppose that there are two channels i and j and $Q = Q_i + Q_j$, $T^* = T_i + T_j$. The Taylor expansion of the exponential is

$$\exp x = 1 + \sum_{p=1}^{\infty} \frac{x^p}{p!} \tag{3.54}$$

Using the energy formula (3.5) and (3.54), we have

$$J_i + J_j - \frac{J^\infty}{\beta} = \frac{1}{|h_i|^2}\sum_{p=1}^{\infty}\frac{\log^p 2}{p!B^{p-1}}\left(\frac{Q_i^p}{T_i^{p-1}} + \frac{|h_j|^2 Q_j^p}{|h_i|^2 T_j^{p-1}} - \frac{(Q_i+Q_j)^p}{(T_i+T_j)^{p-1}}\right) \tag{3.55}$$

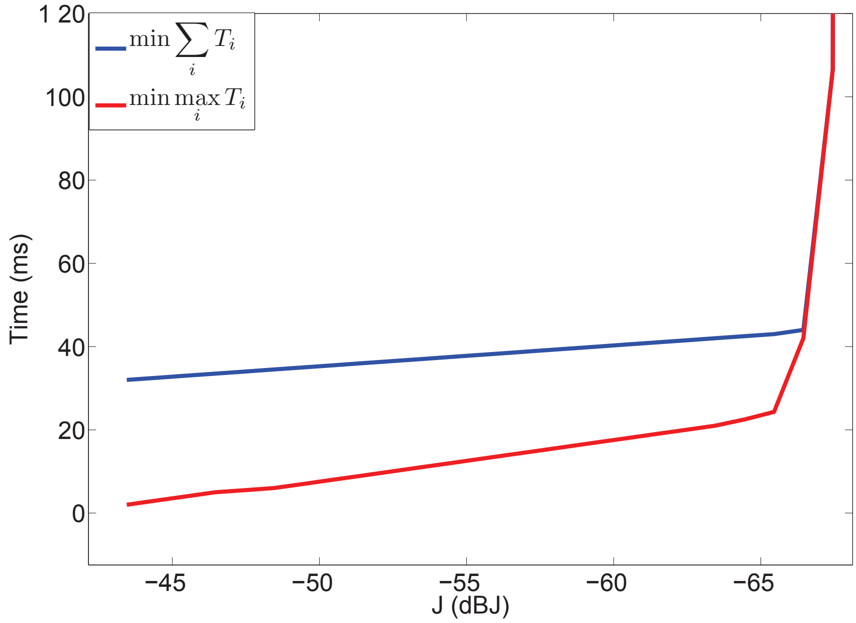

Figure 3.3: Pareto border of energy minimization

or $\forall p \in \mathbb{N}$ and $\{Q_i, Q_j, T_i, T_j\} \in \mathbb{R}^4$

$$\frac{Q_i^p}{T_i^{p-1}} + \frac{Q_j^p}{T_j^{p-1}} + \frac{(Q_i + Q_j)^p}{(T_i + T_j)^{p-1}} \geq 0 \tag{3.56}$$

thus

$$J_i + J_j - \frac{J^\infty}{\beta} \geq 0 \tag{3.57}$$

with equality if and only if $|h_i|^2 = |h_j|^2$ and $Q_j T_i = Q_i T_j$. In this case, the allocation algorithm is simple to achieve. Furthermore, for high values of energy efficiency β, minimizing the time of communication leads to use a single channel, which the total time for communication is minimal. Fig. 3.3 shows the Pareto border of both optimization problems of energy minimization. We observe that when energy consumption is reduced, the optimal communication time $\min \sum_i T_i$ converges to the optimal time communication $\min \max_i Ti$. On the other hand, for high values of energy efficiency β, minimizing the time of cumulative time channel occupancy leads to minimize the maximum time of transmission and the same solution will be used.

3.4.4 Proposed algorithm

Algorithm 1

Input parameters: Q, $\{h_i\}_{i=1}^{n}$, β
for $m = 1 : n$ **do**
  $\mathcal{I} = \{1, \ldots, m\}$
  calculate $w = \frac{\beta}{m \log 2} \sum_{i \in \mathcal{I}} \frac{\max|h_j|^2}{|h_i|^2}$
  if $w < 1/\log(2)$ **then**
    find c_m solution of $2^c - \frac{c}{w} - 1 = 0$
    calculate $T_m = \frac{Q}{m c_m B}$
  end if
end for
$T^* = \min_m T_m$

The function defined in (3.51) has only one root c_0 in $]0; +\infty[$. To obtain the minimal time of transmission, it remains to find the subset of channel $\mathcal{I}$. Note that the higher the channel amplitude the lower the time of transmission. To find the subset $\mathcal{I}$, the channels are sorted in descending order and the Algorithm 1 that solves (3.22) and (3.51) is applied. The proposed algorithm gives the minimum time of transmission under the energy efficiency constraint. This objective is reached after a selection of the channels used for transmission. The green algorithm is used to distribute the data and the available energy among different sub-carriers in an optimal way, to minimize the time of transmission and to maintain the energy efficiency.

3.5 Applications and results

In this section, we present the improvement for both WiMAX and PLC systems.

3.5.1 WiMAX results

In this section, we present some numerical evaluations using parameters of IEEE 802.16 standard [89], in the case of best effort traffic. In particular, our attention is focused on performance comparison between the energy consumed by the WiMAX system and the consumed energy by a green UWT WiMAX system. In our simulation evaluation, the energy consumption is given for one user in one cell. The channel model is the pedestrian channel with the parameters suggested in previous chapter. The channel and system parameters are summarized in Tab. 2.3. The quantity of information to be transmitted is $Q = 1$ Mbit. This limited value allows transmission over quasi-static channel since the maximal transmission time is lower than the coherence time of the pedestrian channel. In that case, it is assumed that the channel transfer function is known at both transmitter and receiver sides. With the UWT WiMAX system, the optimization is carried out performed under energy efficiency constraint and β is fixed to -1 dB. The information allocation is performed using (3.52) and conditions given in (3.22), and the communication time is given by (3.48). The resulting communication system can differ from the system defined by the WiMAX specifications but it is used to point out the capability of UWT approach. Practically, the modulation orders and the bit rates with UWT approach differ from those defined in [89]. UWT could be a good approach for new communication systems that allow low and very low spectral efficiency. Furthermore, the increase of transmission time needs to define new end-to-end delays. The total consumed energy of a conventional WIMAX system and of a green UWT WiMAX system is plotted in Fig. 3.4 for different transmission distances R between the base station and the user. The corresponding transmission time is shown in Fig. 3.5 for various link distances. The capabilities offered by the UWT capproach are compared to the performance obtained with the conventional WiMAX system presented in the previous chapter. The transmitted energy depends on the distance between the base station and the user, and the total energy increases with R. The results in Fig. 3.4 show that the energy used with the conventional WiMAX system is always higher than that with the green UWT WIMAX system. A gain of around 20 dB can be reached. The gain is higher for small distance than for high distance. Significant gains are obtained in favorable channel conditions. Since $\beta = -1$ dB, the consumed energy with the UWT approach is only 1 dB higher than the lower bound of the consumed energy. The energy efficiency of the conventional WiMAX system is given by the algebraic distance of the two curves minus 1 dB. This energy efficiency is then always lower than -7 dB. Let us now compare the transmission time for both solutions, i.e. UWT WiMAX and conventional WiMAX. With UWT, it is clear that to save consumed energy required to send Q bits, it is necessary to transmit information over a long period of time. As shown in Fig. 3.5, for short distance the communication time with UWT is larger than

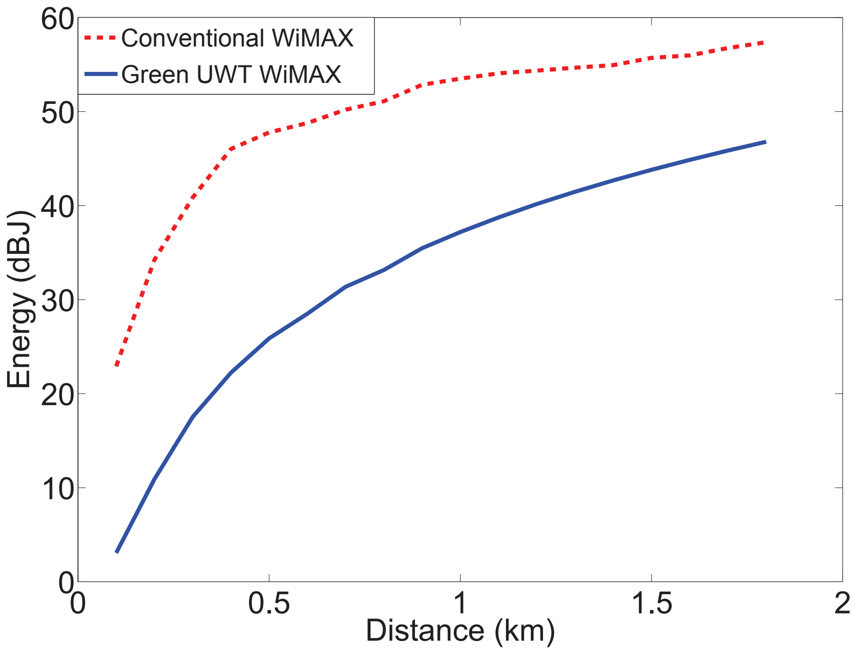

Figure 3.4: Energy consumption of WiMAX systems

with a conventional system. For High distance, the communication time with the UWT approach converge to the maximal value reached with the conventional WiMAX system whereas the energy efficiency obtained with green UWT WiMAX is always higher than that of the conventional WiMAX. For high distance, the number of sub-channels used for both systems is almost similar, that explains the communication time convergence of both systems.

3.5.2 PLC results

In this section, we present numerical evaluations of OFDM transmission in powerline communication. In particular, our attention is focused on performance comparison between the energy consumed by a conventional PLC system presented in previous chapter and the consumed energy that can be reached using the green algorithm. The generated signal is composed of $N = 1024$ sub-carriers transmitted in the band 0–20 MHz. The OFDM symbol duration is 57 µs including a guard interval of 5.8 µs. Perfect synchronization and channel estimation are assumed and the channel transfer function is known at both transmitter and receiver sides. The multi-path channel

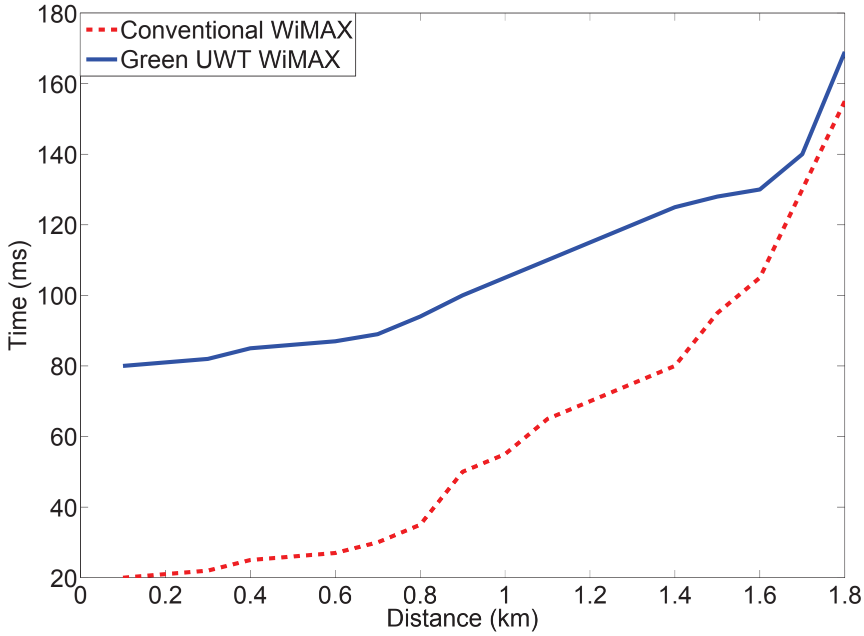

Figure 3.5: Transmission time with WiMAX systems

Bandwidth	0–20 MHz
FFT size	1024
OFDM symbol duration	57 µs
Channel model	Zimmermann 15 paths

Table 3.1: PLC system and channel parameters

model of in-home PLC channel given in the previous chapter is used. The channel and system parameters are summarized in Tab. 3.1. The performance communication systems are computed in the case of perfect channel coding with a system noise margin equal to 0 dB. Unconstrained modulations are used. The green solution is compared to a conventional resource allocation, where the bit rate is maximized under PSD constraint following the well-known water-filling approach presented in the previous chapter. A high background noise level of −110 dBm/Hz is assumed and the signal is transmitted with respect to a flat PSD of −50 dBm/Hz in the case of conventional resource allocation.

The choice of the energy efficiency depends only on three parameters: quantity of

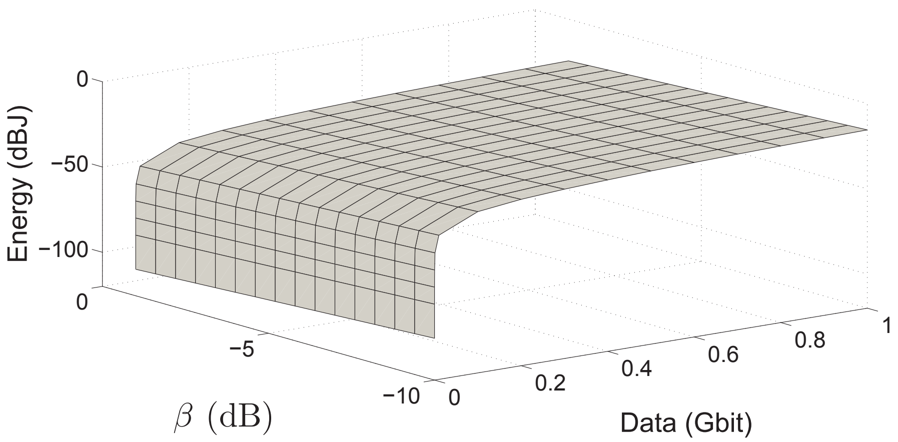

Figure 3.6: Energy vs energy efficiency and quantity of information

information, time of transmission and energy consumption. Fig. 3.6 and Fig. 3.7 represent the energy consumption and the time of transmission versus the energy efficiency β and versus the quantity of information Q for the green algorithm. The time of transmission is calculated with Algorithm 1 and the energy consumption is $\frac{J^{\infty}}{\beta}$ given by (3.34). For these results, the effective bandwidth takes into account the guard interval loss. The time and the energy consumption vary with the quantity of information: the subset $\mathcal{I}$ is then independent of the quantity of information. The increase of energy efficiency β provides a gain of energy consumption but needs more time of transmission.

The optimization is performed under energy efficiency constraint. The information allocation is performed using (3.52) and conditions given in (3.22), and the communication time is given by (3.48). The resulting green communication system can differ from the conventional system but it is used to point out the capability of green optimization. Practically, the modulations and the bit rates in the green algorithm can differ from those defined in the conventional system. Both systems (green and conventional) are compared in Fig. 3.8 and Fig. 3.9. The energy efficiency constraint β is fixed to -1 dB in the case of green resource allocation strategy.

The consumed energy is plotted in Fig. 3.8 for various quantity of information Q. The transmitted energy depends on the quantity of information and the total energy increases with Q. The energy distribution is proportional to the inverse channel gain following (3.47). The results in Fig. 3.8 show that the energy used with conventional system is always higher than with green resource allocation system. A gain around

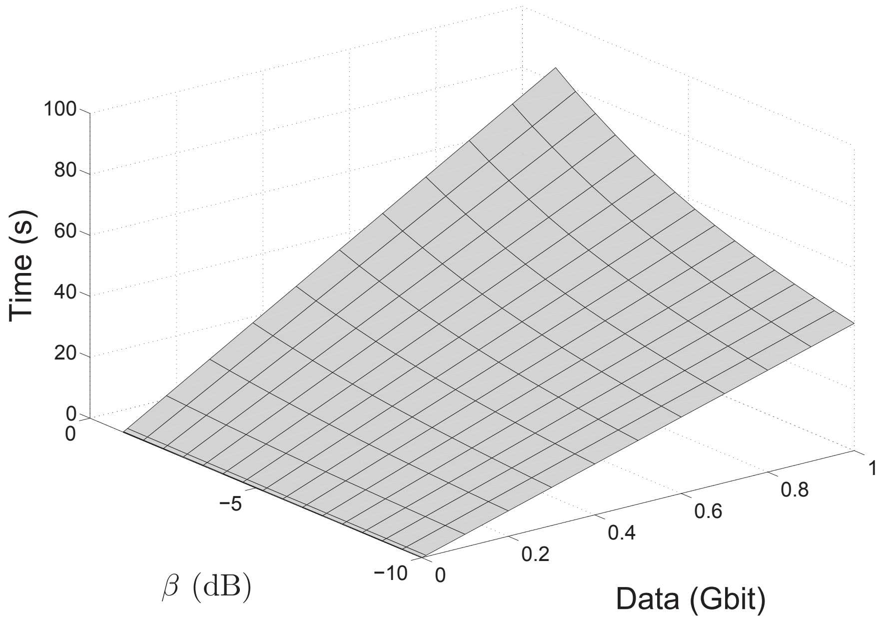

Figure 3.7: Time vs energy efficiency and quantity of information

27 dB can be reached. Furthermore, the green resource allocation strategy satisfies the PSD constraint mentioned in conventional configuration.

Let us now compare the transmission time for both solutions. With the green scheme, it is clear that to save the consumed energy J required to send Q bits, it is necessary to transmit the information over a long period of time, as shown in Fig. 3.9. However, an energy gain factor equal to 500 is then reached while the time of transmission is only multiplied by 10. This green resource allocation strategy provides a huge energy gain with a small increase of the time of transmission.

3.6 Conclusion

In this chapter, we have examined the energy consumption problem in a single user context for single carrier and multi-carrier systems. Both theoretical analysis and simulation results have been provided. A new approach, called UWT, and a new green algorithm for resource allocation have been proposed and defined to save energy. The use of the UWT approach provides the lower bound of transmitted energy consumption which differs from the conventional water-filling solution. A new performance metric,

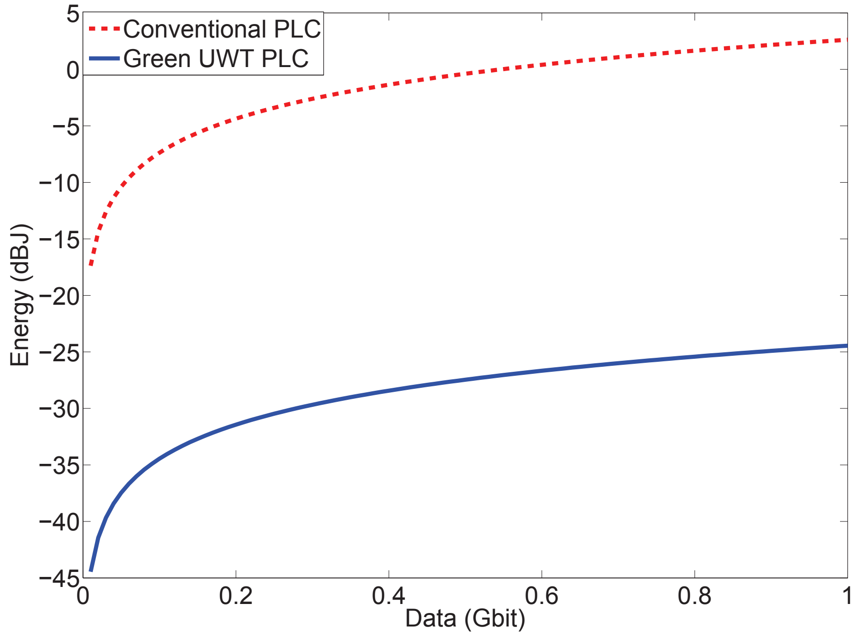

Figure 3.8: Energy consumption in PLC

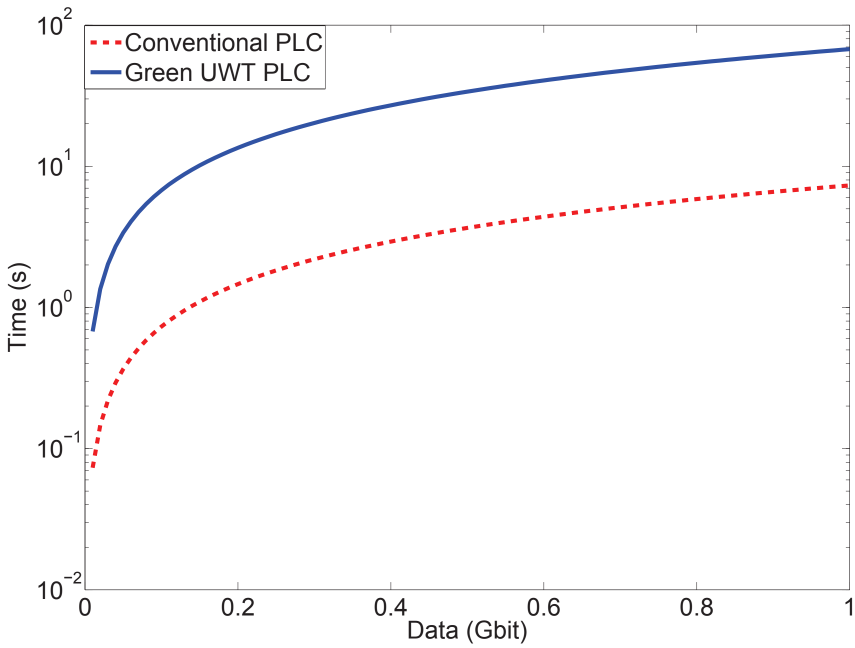

Figure 3.9: Time of transmission in PLC

called the energy efficiency, evaluates the ratio between the transmitted energy consumed by the communication system and the lower bound of this energy consumption has been defined. Simulation results show that UWT is attractive in best effort applications and gains of around 20 dB can be reached for WiMAX communications. In PLC systems, simulation results show that our scheme is attractive for data transmission applications and energetic gains around 27 dB can be reached in PLC communications with only a multiplication of the time of transmission by a factor of 10. This green resource allocation strategy provides a huge energy gain with a weak increase of the transmission time. To be applied, the UWT solution needs new protocols that support new end-to-end delays, and needs communication systems that allow low spectral efficiency. In the next chapter, we will focus on energy performance of UWB communications.

Chapter 4

UWB parameters optimization

4.1 Introduction

The main focus of green radio is to provide new techniques to save energy consumption. According to this trend, ultra wide time approach has been introduced in the previous chapter to save energy. The work in this chapter is focused on UWB communications. The main objective is to define the parameters of UWB systems that minimize the energy consumption in communication systems. The major question for the first part of this chapter is: what are the optimal parameters of the system to minimize energy. The first proposition is to use the shape of impulse UWB systems and then to determine the best parameters for the energy minimization. In this chapter, we focus on Gaussian pulses proposed for UWB communication systems. Different parameters (pulse width, guard time, pulse repetition) are exploited to optimize the performance of communication systems. In addition, we investigate a practical range of pulse repetition interval values and number of pulses per bit in terms of energy efficiency.

Added to the energy efficiency, in the second part, we focus on system capacity maximization. The energy efficiency is fixed by the metric, and the system capacity is maximized. The main approach for UWB system design is to choose the symbol duration larger than the delay of the channel impulse response, in order to avoid inter symbol interference (ISI). However, this approach does not maximize the system capacity. An adaptation of the guard time is a flexible mean of exploiting system resources efficiently especially in multi-path environment. The optimal guard time solution is obtained by complex numerical method. To reduce this complexity, a new optimization method is introduced. This optimization method defines new parameters that provide very close performance to the performance of the optimal system. These parameters link the guard time to the channel characteristics with simple equations. In practical systems, the guard time adaptation is based directly on these parameter values. Simulation results are performed for UWB communications over WiMedia channel and show that the significant gain is achievable with the proposed guard time adaptation.

In the last part of this chapter, we focus on multi-band allocation. The energy minimization problem is presented and a new algorithm is introduced for multi-band allocation.

4.2 Resource allocation and energy optimization in UWB

4.2.1 Problem formulation

To save energy, transceivers can be designed to maximize information per unit energy. The energy consumed to transmit one bit is

$$E_b = (2^{\frac{1}{T_b B}} - 1)\frac{T_b B N_0}{|h|^2} \tag{4.1}$$

where B (Hz) is the channel bandwidth, T_b (second) is the bit duration, N_0 (W/Hz) is the noise spectral density and $|h|^2$ is the gain of the equivalent channel with noise margin. The equivalent channel is composed of the user waveform filter, the channel response and the front-end filter. The formula (4.1) is derived from the formula of the Shannon capacity [71]. In [56], the required minimum energy is reached when the number of degrees of freedom is unlimited. The number of degrees of freedom can be represented by one frequency-time element. With infinite time or infinite bandwidth of transmission, the number of degrees of freedom tends to infinity and the required energy can then be minimized. The asymptotic limits for energy is

$$E_b^{\infty} = \lim_{T_b B \to +\infty} E_b = \frac{N_0 \log 2}{|h|^2} \tag{4.2}$$

For example, the trade-off between bit duration, bandwidth and energy of transmission (4.1) is shown in Fig. 4.1. The energy decreases as the bit duration T_b and the bandwidth B increases. Using the communication model introduced in Chapter 2, (4.1) becomes

$$E_b = (2^{\frac{1}{L(T_p+T_g)\frac{cx}{T_p}}} - 1)\frac{L(T_p+T_g)\frac{cx}{T_p} N_0}{|h|^2} \tag{4.3}$$

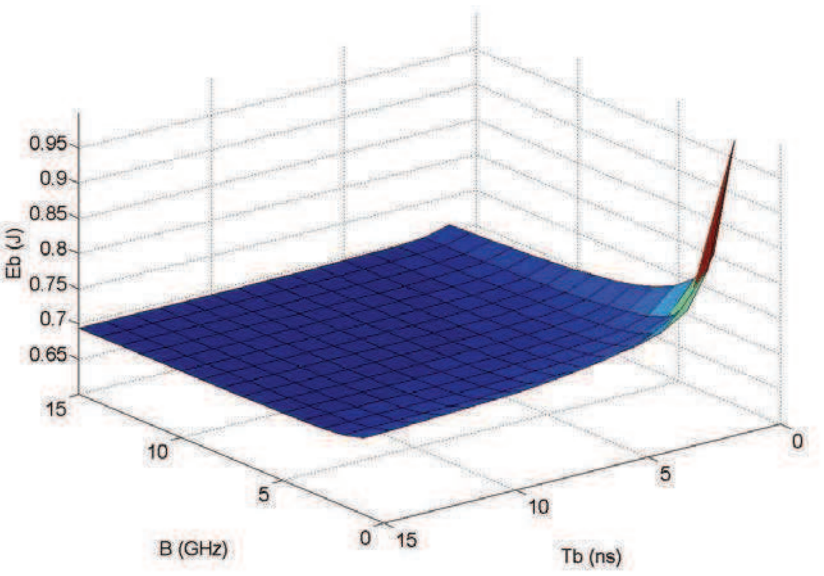

Figure 4.1: Energy vs bandwidth and bit duration

where cx is a constant, that characterizes the relation between the bandwidth and the pulse time T_p, T_g is the guard time and L is the number of pulse repetitions. The required minimum energy is reached when $cxL(1 + \frac{T_g}{T_p})$ tends to $+\infty$. The minimization of energy required to transmit one bit needs numerous pulse repetitions, huge bandwidth or very small pulse time. The communication system with huge bandwidth is the known as UWB approach [56]. The huge pulse repetition is known as new approach introduced in the revious chapter and called UWT. The last equation means that to save energy, the system requires a huge bit duration. Our objective is to combine both approaches (UWT and UWB) to obtain more freedom in the pulse design problem.

4.2.2 Energy efficiency and system parameters

In the last years, UWB has been developped for many applications, such as wireless personal area networks (WPAN) [119]. Using short pulses, UWB baseband transmissions enable rich multi-path diversity and can be demodulated with low complex receivers [78]. Several researches have been performed on the problem of pulse design for UWB communications [119]. In our study, we combine the UWB and the UWT approaches to minimize the energy consumption.

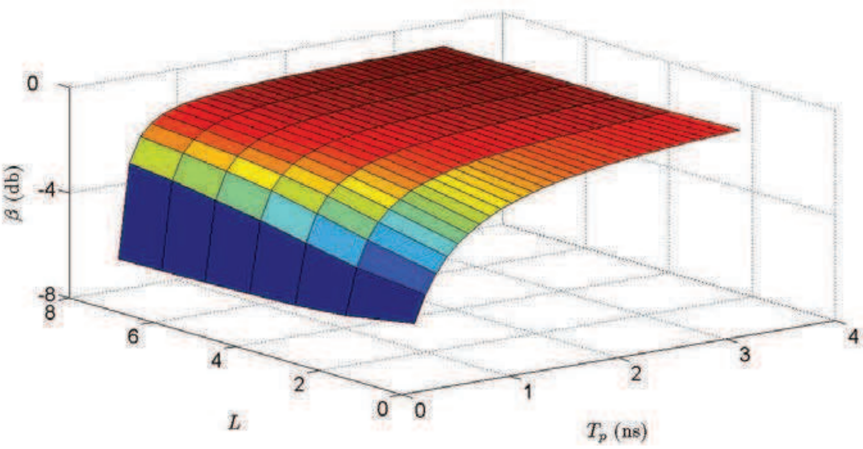

Figure 4.2: Energy efficiency vs the pulse repetition and pulse time

The energy saving needs infinite time or infinite bandwidth. To overcome the drawback of infinite bit duration and infinite bandwidth, we define one operating point of communication system in terms of transmitted energy consumption. We then use the performance measure β introduced previously

$$\beta = \frac{E_b^{\infty}}{E_b} \tag{4.4}$$

The resource allocation objective is to find the combination of $\{T_p, T_g, L\}$ that satisfy the energy constraint β and that maximize the bit-rate. The optimization problem can be written as follows

$$\min T_b \quad \text{subject to} \;\; J = J(\beta) \tag{4.5}$$

Using Fig. 4.2 and Fig. 4.3, several combinations of bandwidth, guard time and pulse repetition give the solution of the problem (4.5). Fig. 4.2 and Fig. 4.3 show the energy efficiency β versus the different parameters of the system, when cx is equal to 5.

4.3 QoS and energy efficiency

While saving energy, a quality of service (QoS) which corresponds to a given bit error rate (BER) must be guaranteed. Then, the BER constraint is used for the system optimization in order to avoid any unnecessary packet loss and to guarantee a certain

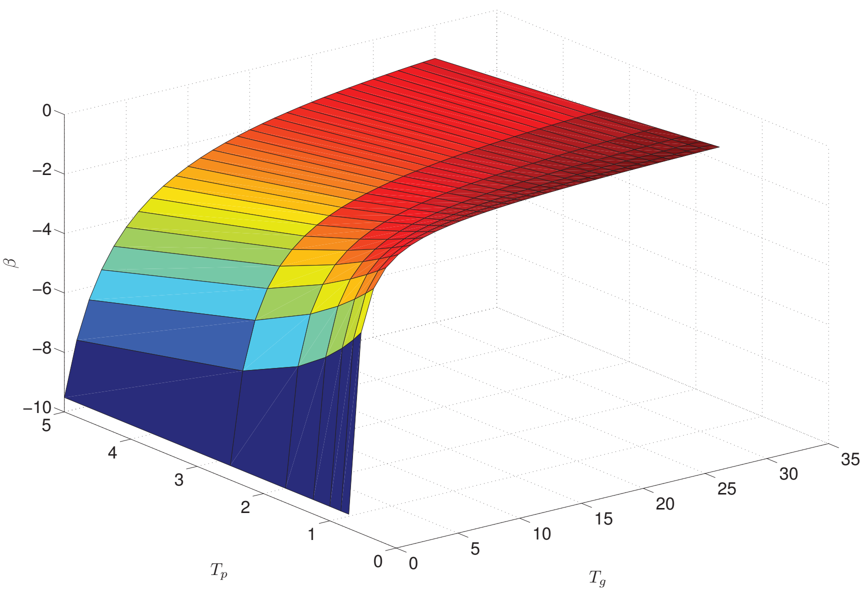

Figure 4.3: Energy efficiency vs the pulse time and guard time

level of quality of service. Furthermore, the system optimization becomes

$$\min T_b \quad \text{subject to} \begin{cases} J = J(\beta) \\ BER_i = BER_a \end{cases} \tag{4.6}$$

where BER_i is average BER, and BER_a is average BER constraint. In the case of BPSK, the approximative formula of BER is

$$BER = Q(\sqrt{2E_b/N_0}) \tag{4.7}$$

where Q-function can be expressed in terms of the complementary error function $erfc$ as

$$Q(x) = \frac{1}{2}erfc(\frac{x}{\sqrt{2}}) \tag{4.8}$$

and the complementary error function is defined as

$$Q(x) = \frac{2}{\sqrt{\pi}}\int_x^\infty \exp(-t^2)dt \tag{4.9}$$

The new algorithm for resource allocation is proposed to minimize bit duration under energy efficiency and BER constraints. The minimization problem is divided into two sub problems. We minimize the pulse time under energy constraint and the guard time or pulse repetition to respect the BER constraint.

$$(4.6) \Rightarrow \begin{cases} \min T_p & \text{subject to} \quad E_b = E_b(\beta) \\ \min T_g & \text{subject to} \quad BER_i = BER \end{cases} \quad \text{or} \quad \begin{cases} \min T_p & \text{subject to} \quad E_b = E_b(\beta) \\ \min L & \text{subject to} \quad BER_i = BER \end{cases}$$

The detailed calculation of our solution is given in Appendix A. The proposed solution gives the system parameters as follows. The pulse time is

$$T_p = \frac{-r \log 2}{B(rW(-\frac{2^{-\frac{1}{r}} \log 2}{r}) - \log 2)} \tag{4.10}$$

where $r = \frac{E_b(\beta)|h|^2}{N_0}$ and W is the Lambert function. The guard time is

$$T_g = \frac{-u \log 2}{B(uW(-\frac{2^{-\frac{1}{u}} \log 2}{u}) - \log 2)} - T_p \tag{4.11}$$

where

$$u = |h|^2 (Q^{-1}(BER))^2 \tag{4.12}$$

The number of pulse repetitions is

$$L = \frac{-n \log 2}{T_p B(nW(-\frac{2^{-\frac{1}{n}} \log 2}{n}) - \log 2)} \tag{4.13}$$

where

$$n = |h|^2 (Q^{-1}(BER))^2 \tag{4.14}$$

The new optimization provides the optimum values of the system under BER and energy efficiency constraints. The BER constraint is plotted in Fig. 4.4 and Fig. 4.5 versus the system parameters $\{T_p, T_g, L\}$.

4.4 Capacity optimization

Gaussian monocycle was initially proposed and has been widely used for UWB applications [78, 119]. The symbol duration of UWB system is generally larger than the maximum delay spread such that the inter-symbol interference can be neglected [120, 121]. To maximize the capacity, the system does not necessarily need a huge guard time.

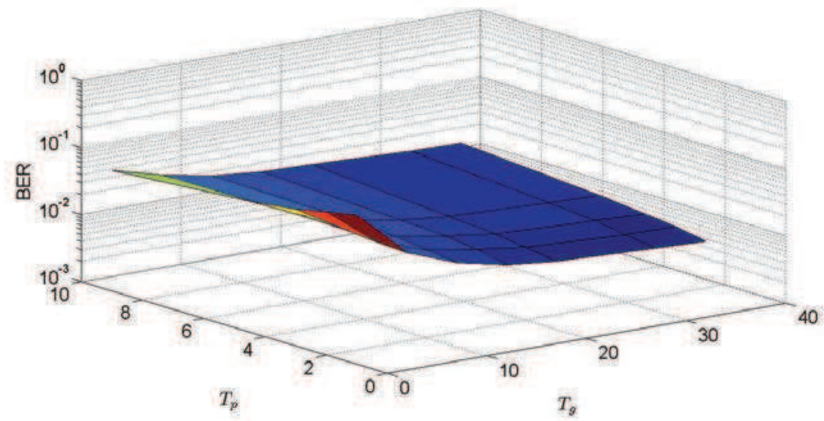

Figure 4.4: BER vs T_p and T_g

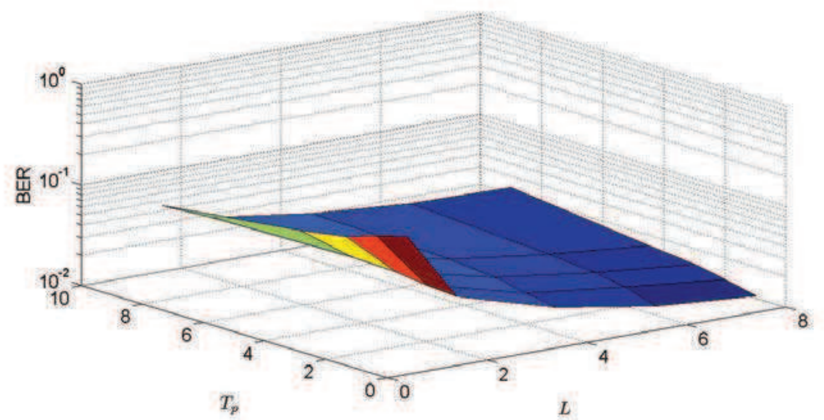

Figure 4.5: BER vs T_p and L

That is, the system can tolerate an amount of interference in order to reduce the guard time, and the system capacity can be improved. An adaptation of guard time is a flexible mean to exploit system resources efficiently especially in multi-path environment. The case of a guard interval shorter than the channel impulse response has been considered with OFDM systems [122, 123]. In this chapter we report an analysis of the guard time optimization problem. The optimization problem is complex and requires a large computation time. Development of a new optimization method to reduce the system complexity and to improve the capacity with guard time adaptation is needed. One of the efficient methods is to define new parameters that provide very close performances to the optimal configuration. These parameters link the guard time to the channel characteristics with simple equations. To this end, three measures of the channel are considered. These measures are the root mean square (RMS) delay spread, the received energy and the energy of the interference. This choice is motivated by the fact that these measures can easily be obtained in communication systems. The optimization method provides the parameters value that will be used directly in the practical systems. These parameters values facilitate the guard time calculation and thus avoids the cost associated with guard time optimization. The guard time can be flexibly adjusted by this method for any channel.

4.4.1 Capacity calculation

To evaluate the impact of the guard time on the system performance, we define the optimum value of guard time that maximizes the system capacity. The capacity is defined as the maximum of the mutual information

$$C = \max_{p(x)} I(X, Y) \tag{4.15}$$

In the case of BPSK, the mutual information is maximized for equi-probable signaling. Let us now compute the mutual information as a function of the bit energy E_b, the power spectral density of noise N_0 and the interference. The mutual information is

$$I(X, Y) = S(Y) - S(Y/X) \tag{4.16}$$

where the both entropies are defined as [124]

$$S(Y/X) = \frac{1}{2} \log_2 2\pi e \tag{4.17}$$

and

$$S(Y) = -E[\log_2 p(Y)] \tag{4.18}$$

where the probability $p(Y)$ is defined as

$$p(Y) = \Big(\frac{1}{2^{n+1}}\frac{1}{\sqrt{2\pi}}\sum_{s=1}^{2}\sum_{i=1}^{2^n}\exp(-\frac{(y-b_sA+\sum_{j=1}^{n}a_j\alpha_{j,i})^2}{2})\Big) \tag{4.19}$$

where n is the number of bits that interfere, a_j is the interference amplitude of bit j, $\alpha_{i,j}$ is the matrix of possible cases of interference with dimensions $\{n, 2^n\}$. The detailed calculation for capacity expressions is given in Appendix B. Then, the capacity measured in bit/s/Hz achieved in the case of BPSK is

$$\begin{aligned} C(T_g) = -\frac{1}{T_bB}\Big(E\Big[\log_2\Big(\frac{1}{2^{n+1}}\frac{1}{\sqrt{2\pi}}\sum_{s=1}^{2}\sum_{i=1}^{2^n}\exp(\\ -\frac{(y-b_sA+\sum_{j=1}^{n}a_j\alpha_{j,i})^2}{2})\Big)\Big] - \frac{1}{2}\log_2(2\pi e)\Big) \end{aligned} \tag{4.20}$$

where B is the channel bandwidth. The Monte Carlo integration is needed to compute $C(T_g)$. The optimal value of the guard time is given by

$$T_g^* = \arg\max_{T_g} C(T_g) \tag{4.21}$$

The evaluation of the argument in (4.21) is computationally hard because it requires a Monte Carlo computation for each guard time value. Therefore, the attractive solution is to define a new optimization method with low complexity.

4.4.2 Guard time optimization

4.4.2.1 Optimization Method

The optimization problem in (4.21) tends to be complex and often requires large amounts of computation time. In this section, we describe in detail the optimization method. The objective is to find a parameter value, which simplify the guard time optimization. In practical systems, the guard time adaptation is based directly on this parameter value.

The first step of optimization method consists in analysing the channel model and calculates the optimal parameter for each realization of the impulse responses. The second step of optimization is to define the parameter values of the channel. The last step consists in comparing different measures used and defines the best parameter for the UWB systems.

The present optimization consists of an initial step that determines the characteristics of the channel. The optimal guard time depends on each channel realization. In order to obtain global channel characteristics, several realizations will be considered for each channel model. The initial step includes the steps of calculating capacity, defining the optimal guard time and calculating the optimal parameters linking the guard time and the chosen measure. The measures are the RMS delay spread, the received energy and the energy interference. The relation between the optimal parameter ρ_λ, the optimal guard time and the measure $\mathcal{L}$ for each channel realization is defined as

$$\rho_\lambda = f_{\mathcal{L}}(T_g^*, \lambda) \tag{4.22}$$

where λ is the value of the measure $\mathcal{L}$, and $f_{\mathcal{L}}(.)$ the function that links λ, T_g^* and ρ_λ.

The second step permits to define a sub-optimal guard time T_g^* that links the realization λ of the measure $\mathcal{L}$ with a mean parameter $\bar{\rho}_\lambda$. The parameter $\bar{\rho}_\lambda$ characterizes each channel model. This step allows to avoid the cost associated to capacity calculation. Then, the guard time is obtained directly by the parameter $\bar{\rho}_\lambda$ and the value of the measure λ. The guard time is defined as

$$\hat{T}_g^* = f_{\mathcal{L}}^{-1}(\bar{\rho}_\lambda, \lambda) \tag{4.23}$$

The last step is dedicated to the performance evaluation. Firstly, the capacity corresponding to the chosen parameters is calculated. Secondly, the relative error capacity is used to compare the performance of all parameters. The last step of optimization is to select the best parameter value and measure among all possibilities. The optimization method is summarized as follows:

- Define the characteristics of each channel
    1. Capacity calculation using (4.20)
    2. Optimal guard time calculation using (4.21)
    3. Parameter value calculation using (4.22)
- Fix one parameter value for all channel realizations in each channel model

1. Guard time calculation using (4.23) for each channel

- Performance evaluation for each channel

1. Calculate the capacity corresponding to the parameter value
2. Calculate the relative error between the capacity of parameter value and the optimal capacity of the system

4.4.3 Parameters adjustment for guard time optimization

In this section, the parameters linking the optimal guard time and the measures are presented.

4.4.3.1 Delay spread metric

The delay spread is a key measure of the channel. Delay spread is an effective indicator that makes it easy to evaluate multi-path propagation. The interference causes in a digital system is mainly related to this measure. Practically, delay spread value is directly related to the propagation environment. Obviously, delay spread is not constant in wireless mobile communication channel and its values can change depending on the terrain, the distance and the antenna directivity. The first parameter proposed is based on the evaluation of RMS delay spread [123]. The RMS delay spread is defined as

$$\sigma = \sqrt{\frac{\int_0^\infty (\tau - \mu)|h(\tau)|^2 d\tau}{\int_0^\infty A_c(\tau) d\tau}} \tag{4.24}$$

and the average delay spread is

$$\mu = \frac{\int_0^\infty \tau A_c(\tau) d\tau}{\int_0^\infty A_c(\tau) d\tau} \tag{4.25}$$

where $|h(\tau)|^2$ is the power delay profile with τ the multi-path delay. The significant fraction of the received energy is captured within $\rho_1 \sigma$ with $\rho_1 > 0$ [125]. Conversely, when $T_b \gg \sigma$ the system experiences negligible inter-symbol interference. The measure $\mathcal{L}$ is the RMS delay and λ in (4.22) is σ. The parameter linking the guard time and the RMS delay spread is given as

$$\rho_1 = \frac{T_g^*}{\sigma - T_p} \tag{4.26}$$

where T_g^* is defined by (4.21) and $f_{\mathcal{L}}$ by (4.22) is a rational function.

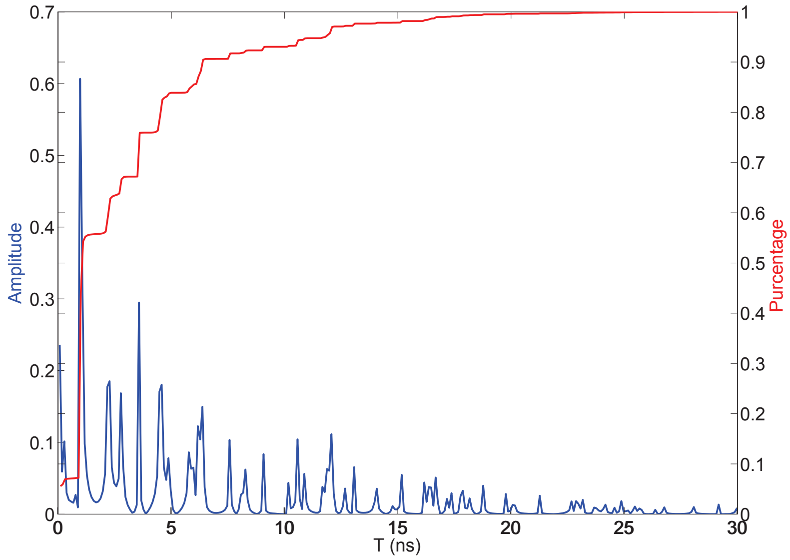

Figure 4.6: An example of multi-path CM1 channel impulse response and the CDF of the received energy

4.4.3.2 Energy of channel approximation

In this section, we define a parameter that links the optimal guard time with the channel multi-path components. Fig. 4.6 shows an example of multi-path CM1 channel impulse response, where the red curve is the cumulative distribution function (CDF) of the received energy. The measure $\mathcal{L}$ is the received energy. In this case the optimal guard time adaptation is defined by a parameter ρ_2. This parameter is the percentage of the received energy that corresponds to the optimal guard time. The parameter linking the guard time and the channel energy is

$$\rho_2 = \frac{\sum_{i=1}^{\lfloor \frac{T_g^* + T_p}{T_s} \rfloor} |h_i|^2}{\sum_{i=1}^{N} |h_i|^2} \tag{4.27}$$

where T_s is the sampling time and N is the length of the channel. The parameter value ρ_2 is an element on the interval $(0, 1]$.

4.4.3.3 System capacity approximation

The third parameter for the guard time optimization is obtained by using the capacity approximation. To evaluate the impact of guard time on the system performance, we use the approximate formula of capacity where the interference is considered Gaussian

$$C_I = \frac{1}{T_b B} \log 2(1 + \frac{SINR}{\gamma}) \tag{4.28}$$

where γ is a gap factor for practical modulation. The target of optimization is to define the sub-optimal guard time

$$T_g^{'} = \arg\max_{T_g} C_I \tag{4.29}$$

then

$$T_g^{'} = \arg\max_{T_g} \left((1 + \frac{SINR}{\gamma})^{\frac{1}{T_b B}} \right) \tag{4.30}$$

The lower bound of (4.30) is obtained with Bernoulli inequality

$$(1 + \frac{SINR}{\gamma})^{\frac{1}{T_b B}} \geq (1 + \frac{1}{T_b B} \frac{SINR}{\gamma}) \tag{4.31}$$

A practical simplification method is to use this lower bound. Then, the sub-optimal guard time is

$$T_g^{'} = \arg\max_{T_g} \frac{SINR}{\gamma T_b B} \tag{4.32}$$

The sub-optimal guard time in (4.32) has a computational advantage over (4.21). Firstly, the computation of the logarithm is avoided. Secondly, (4.32) requires only the evaluation of the interference power for different values of guard time instead of the computation of the capacity as in (4.21). The last parameter is defined as

$$\rho_3 = \frac{T_g^*}{T_g^{'}} \tag{4.33}$$

where T_g^* is defined by (4.21).

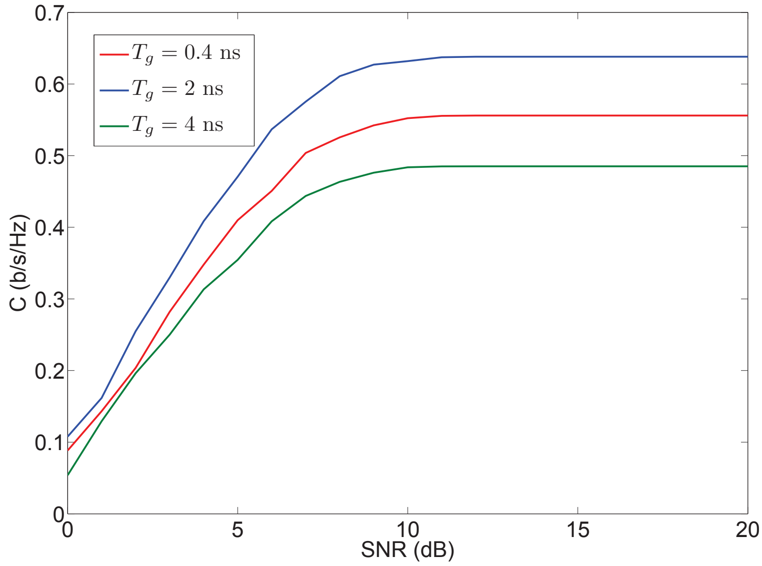

Figure 4.7: Capacity vs SNR over CM1 channel

4.4.4 Applications and simulation results

4.4.4.1 Capacity optimization

Firstly, we analyze the capacity of the UWB communications. In this analysis, we show the relationship between the guard time and the system capacity using (4.20). Fig. 4.7 shows the capacity versus the SNR for three guard time values over CM1 channel model. The maximum system capacity is achieved for the value of $T_g = 2$ ns.

Fig. 4.8 shows the capacity versus the guard time for one channel realization. The SNR is fixed to 10 dB for this simulation. The capacity increases as the guard time increases up to the maximum capacity achieved. The maximum capacity corresponds to the optimal guard time T_g^* of the system. The optimal guard time is different for each channel model. In CM1 channel, the optimal guard time value is 2 ns. This value increases to 5 ns for CM2 channel, to 8 ns for CM3 channel and to 11 ns for CM4 channel. Furthermore, where the guard time of the system is larger than T_g^*, the system capacity decreases as the guard time increases. Without interference, the capacity decreases as the guard time increases. With high level of interference, the capacity increases as interference decreases. Then, the compromise of both interference and guard time explains the form of the curve in Fig. 4.8. The maximum achieved

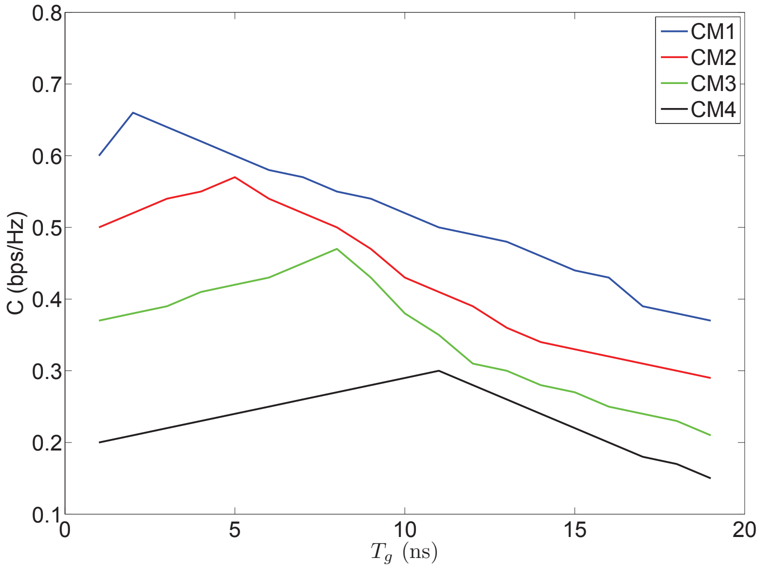

Figure 4.8: Capacity vs guard time

capacity and the optimal guard time are different for each realization of channels. Nevertheless, the system capacities with CM1 channel model are superior than the system capacities with other channel models. The CM1 channel model occurs a low multi-path delay spread. Then, the maximum capacity is reached with the minimum guard time. The high multi-path delay spread is occurred by CM4 channel model. Then, the maximum capacity is obtained with higher guard time.

We now turn our attention to the comparison between the system with guard time adaptation and conventional system. The conventional system takes a fixed guard time. This guard time is larger than the maximum excess delay τ_{max} of all the channels in each classe. Tab. 4.1 summarizes the capacity and the bit duration for both systems with one channel realization.

	$T_b(T_g^*)$ ns	$C(T_g^*)$	$T_b(\tau_{max})$ ns	$C(\tau_{max})$
CM1	7	0.66	40	0.2
CM2	10	0.57	60	0.13
CM3	13	0.47	80	0.08
CM4	16	0.3	120	0.045

Table 4.1: Capacity comparison

The adaptation of the guard time leads to significant performance improvements. The gain factor achieved with guard time adaptation is equal to 3 in CM1 channel model. This gain increases to 4.38 in CM2 channel model, to 5.88 in CM3 channel model and to 6.66 in CM4 channel model. Comparison of the results in Tab. 4.1 reveals that the adaptation of the guard time yields significant gains compared to a fixed guard time. Then, an adaptation of guard time is a flexible mean to improve a system capacity.

4.4.4.2 Parameters optimization

As shown previously, the optimal guard time duration depends on channel models. It is required that the transmitter calculates the value of the guard time for each channel realization which is in practice difficult to apply. In this section we provide a general analysis for guard time and parameter optimization for all channel models. We follow the steps of the optimization method presented in Section 4.4.2.1. Fig. 4.9 shows the measured CDF (cumulative distribution function) of the optimal capacity according to (4.20). For CM1 channel model, the guard time is always shorter than 6 ns. This value increases to 8.5 ns for CM2 channel model, to 14.5 ns for CM3 channel model and to 20 ns for CM4 channel model. The results reveal that the optimal guard time is a function of both the channel model and the specific channel impulse response. The maximum system capacity is obtained with interference.

Now, we analyze the parameters proposed in Section 4.4.3. Fig. 4.10 shows the measured CDF of the parameter ρ_1 according to (4.26). For CM1 channel model, the value of ρ_1 is in the interval $[0.89, 1]$. The endpoints of the interval decrease to $[0.84, 0.97]$ for CM2 channel model, to $[0.76, 0.89]$ for CM3 channel model and to $[0.72, 0.86]$ for CM4 channel model. Fig. 4.11 shows the measured CDF of the parameter ρ_2 according to (4.27). For CM1 channel model, the value of ρ_2 is in the interval $[0.7, 1]$. The endpoints of the interval decrease to $[0.6, 0.85]$ for CM2 channel model, to $[0.58, 0.85]$ for CM3 channel model and to $[0.5, 0.8]$ for CM4 channel model. Fig. 4.12 shows the measured CDF of the parameter ρ_3 according to (4.32). For CM1 channel model, the value of ρ_3 is in the interval $[0.53, 3]$. The supremum of the interval increases to 4 for CM2 channel model, to 5.5 for CM3 channel model and to 7 for CM4 channel model. Given those values of parameters presented in Fig. 4.10, 4.11 and 4.12, the global value

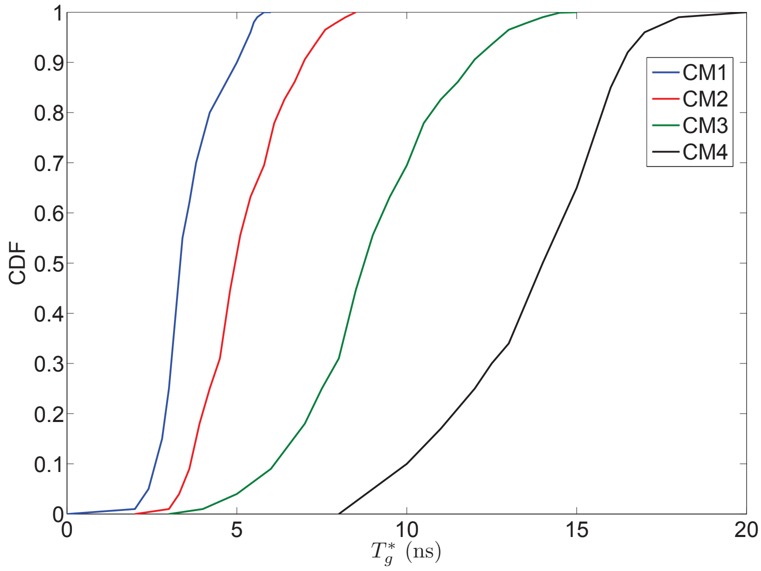

Figure 4.9: CDF of the optimal capacity

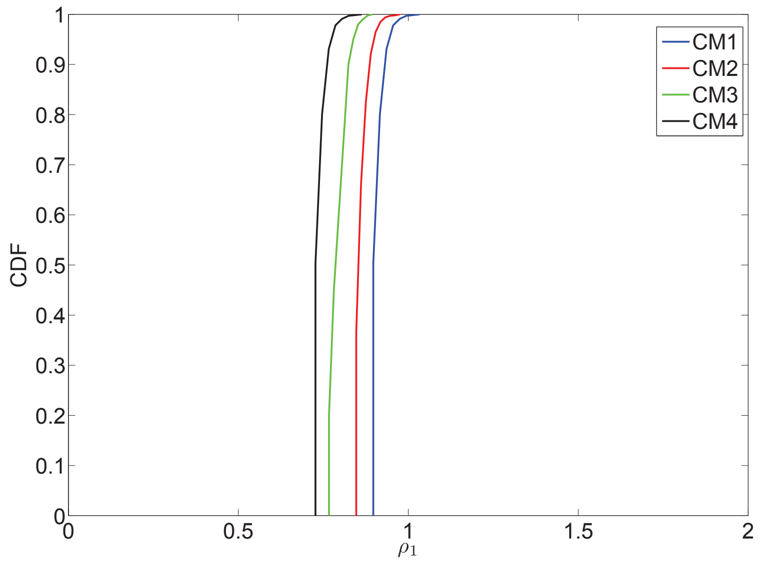

Figure 4.10: CDF of parameter ρ_1

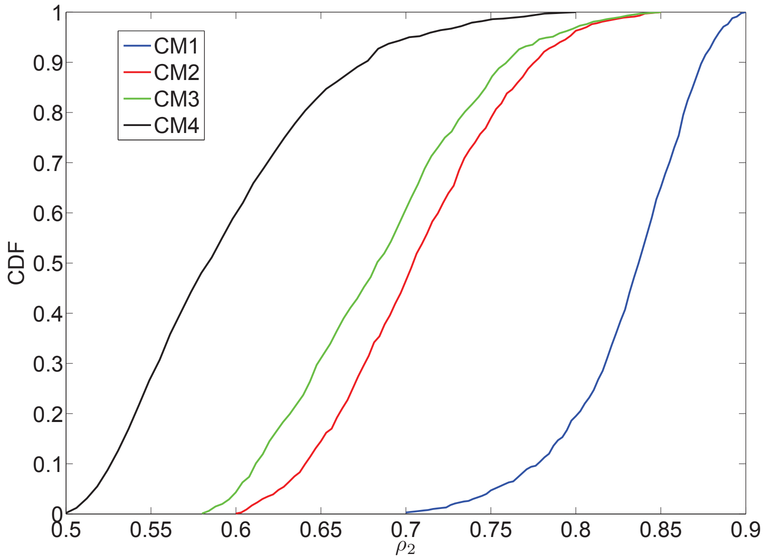

Figure 4.11: CDF of parameter ρ_2

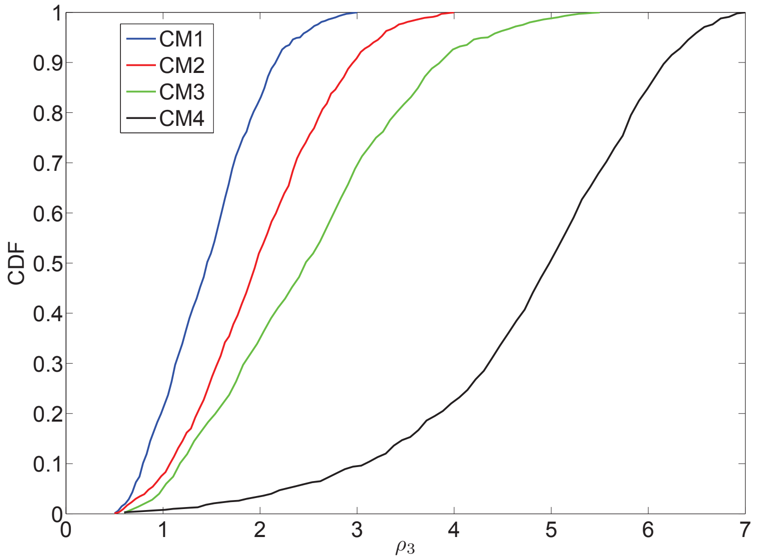

Figure 4.12: CDF of parameter ρ_3

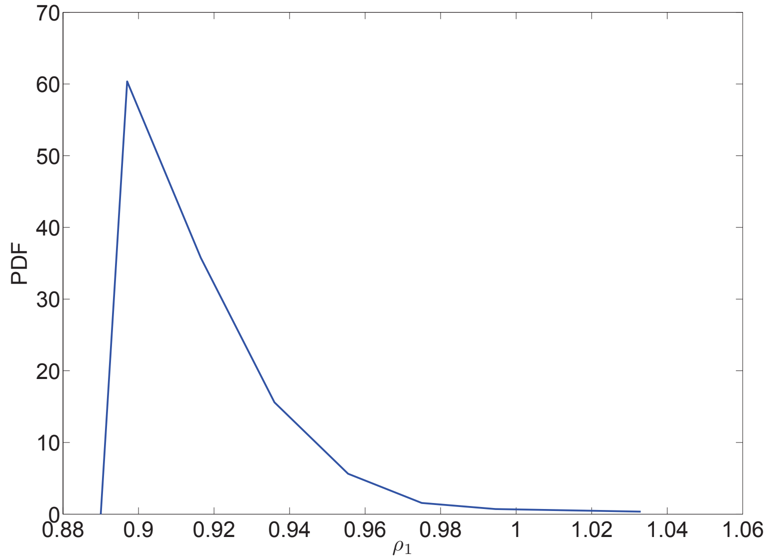

Figure 4.13: PDF of parameter ρ_1

of parameters are provided. The value of parameter ρ_1 is less variable than the parameter value ρ_2 and ρ_3 for all channel models. Very similar results are obtained with ρ_1 and ρ_3 for all channel models. However, the distribution of parameter value ρ_2 depends much more on the channel.

We also plot the probability distribution function (PDF) for all parameters. Fig. 4.13 shows the PDF for the first parameter ρ_1. As example for CM1, the value ρ_1 is given by a distribution of mean 0.94 and standard deviation 0.04. In Fig. 4.14, the PDF for ρ_2 is plotted. The value ρ_2 is given by a distribution of mean 0.83 and standard deviation 0.06. Fig. 4.15 shows the PDF for ρ_3. The value ρ_3 is given by a distribution of mean 1.72 and standard deviation 0.9. Parameter ρ_1 is focused in a very tight interval. However, ρ_2 and ρ_3 are spread over a large interval. The best performance can be given with RMS delay parameter. It is shown that the minimum deviation is reached. However analyse more deeply the results, the relative error capacity will be calculated in the next section to validate our approach.

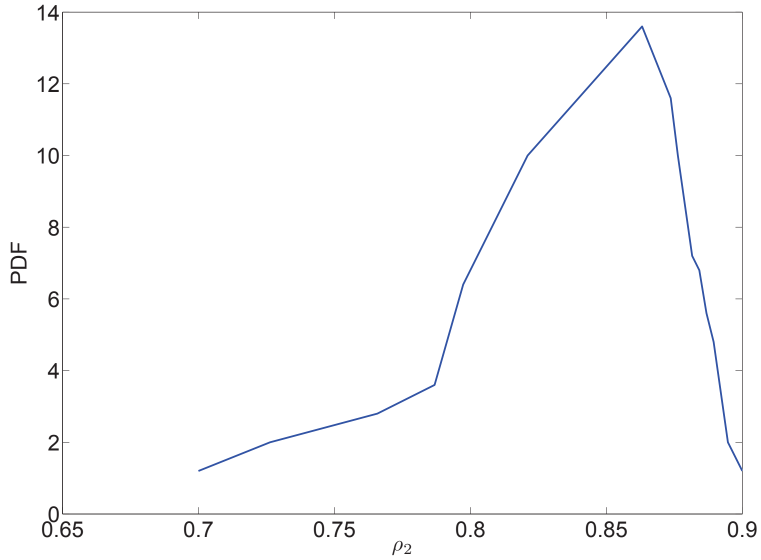

Figure 4.14: PDF of parameter ρ_2

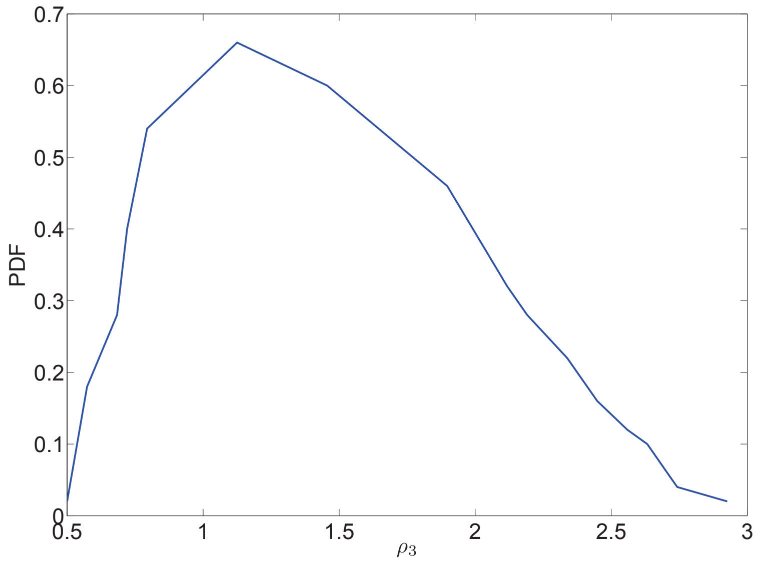

Figure 4.15: PDF of parameter ρ_3

4.4.4.3 Performance evaluation and validation

To obtain the optimal guard time, it remains to find the value of the parameters. It is useful to fix one value of the parameter ρ_λ and to adapt the transmitter to this value. Our strategy is to determine the guard time length directly from the value of the used parameter and thus to avoid the cost associated with the capacity calculation.

The basic idea to determine the value of parameter is to take the median value of CDF. It is clear that the maximal system capacity is not achieved in all cases of transmission. But, the capacity is very close to the optimal value. The objective of pulse design is simply to use the median value of the parameter and to define the guard time adapted to user channel conditions. The pulse design process is based on the median value of the parameters presented in Tab. 4.2.

	CM1	CM2	CM3	CM4
ρ_1	0.89	0.86	0.79	0.72
ρ_2	0.84	0.70	0.68	0.58
ρ_3	1.45	1.96	2.47	5

Table 4.2: Performance parameters value

We compare the relative error capacity for all parameters in Fig. 4.16. This relative error capacity measures system capacity loss and is defined as

$$\epsilon_c(\bar{\rho}_\lambda) = \frac{C(T_g^*) - C(T_g(\bar{\rho}_\lambda))}{C(T_g^*)} \tag{4.34}$$

where $\bar{\rho}_\lambda$ is the median value of the parameter. Fig. 4.16 shows the measured CDF of the relative error capacity for the three parameters. Results are given for the channel model CM1. Both parameters ρ_1 and ρ_2 provide less error than ρ_3. The maximum relative error capacity value is obtained with ρ_1 equal to 0.12, ρ_2 equal to 0.16 and ρ_3 equal to 0.25. The probability that the maximum capacity achieved is 52% with ρ_1 and ρ_3 and 9% with ρ_3. The optimal guard time is obtained in 52% of cases with ρ_1 and ρ_2. Although both parameters possess the same capability to withstand capacity errors. In the other channel models, the maximum relative error capacity value s obtained with ρ_1 equal to 0.13 in CM2 channel model, 0.14 in CM3 channel model and 0.15 in CM4 channel model. For ρ_2, the maximum relative error capacity value is 0.16 in CM2 channel model, 0.18 in CM3 channel model and 0.19 with CM4 channel model. For ρ_3,

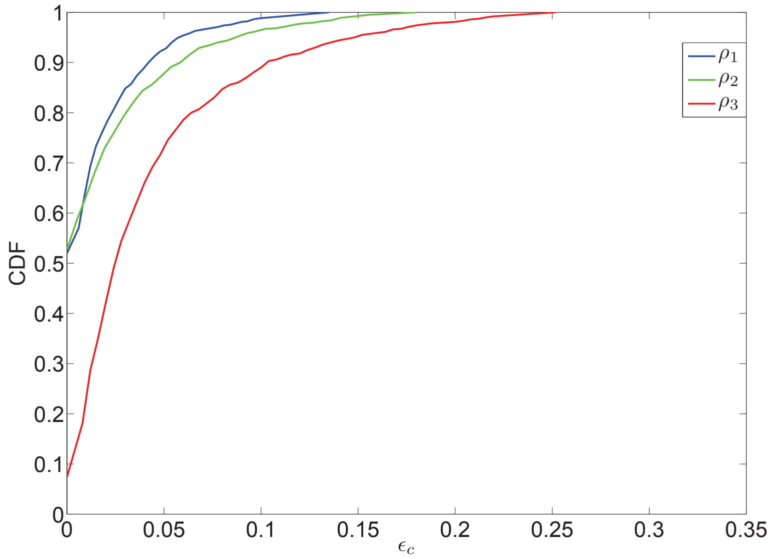

Figure 4.16: CDF of error for all parameters

the maximum relative error capacity value is 0.26 in CM2 channel model, 0.28 in CM3 channel model and 0.30 in CM4 channel model. The three parameters are capable to reach the optimal performance but with a different rate. The relative error capacity for all channel models are summarized in Tab.4.3. The optimal guard time is obtained with 48% of cases with ρ_1 and ρ_2 in CM2 channel model, 45% in CM3 channel model and 44% in CM4 channel model. The proposed method optimization facilitates the guard time design and improves the system performances. Notably, the results with parameters ρ_1 and ρ_2 are close to the optimal system performance and better than those obtained with parameter ρ_3.

	CM1	CM2	CM3	CM4
ρ_1	0.12	0.13	0.14	0.15
ρ_2	0.16	0.18	0.19	0.19
ρ_3	0.25	0.26	0.28	0.30

Table 4.3: The maximum error capacity

4.5 MB resource management principle

4.5.1 Problem formulation

Recently, with the high demand of data transfers, the multi-band technique is used for communication systems. The UWB systems can be either single-band, or, multi-band. The IEEE is undergoing a process of extensive discussions on UWB standard 802.15.3a. A multi-band system is a particular type of multi-carrier system where the transmitted bandwidth is divided into sub-bands that are transmitted in parallel. The solution is based on a sequential use of sub-bands through a frequency-hopping. In a MB-UWB system, a chunk of bandwidth is divided into multiple sub-bands each with 528 MHz bandwidth as presented in Chapter 2. The division into sub-bands permits a better control of the spectral occupancy of the transmitted signal. Two models of resource allocation are studied hereafter. The first one choses the adjacent sub-bands. With the second one, the best sub-bands are chosen according to channel response. It's assumed that channel state information is available at the transmitters. Hence, our target is to define the best allocation that minimizes the bit duration under energy efficiency constraint. The goal of this solution is to exploit the resource in the frequency and time domains. The optimization problem is defined as

$$\min T_b \quad \text{subject to} \begin{cases} \sum_{i=1}^{n} E_{b_i} = E_b(\beta) \\ E_{b_i} \geq 0 \end{cases} . \tag{4.35}$$

In this case under energy efficiency constraint, we define the required bandwidth for transmission. The target is to define the best adjacent sub-bands for transmission. The processes of the first algorithm named Algorithm 2 proposed is as follows: the energy efficiency constraint of the system is achieved when the best channels are used. Our target is to define the best adjacent sub-bands that minimizes the bit duration corresponding to energy efficiency β. Then, the algorithm chooses the best adjacent sub-bands and the minimum time of transmission is calculated using the formula given in Appendix A. With thus solution, it is easy to define the parameters of the pulse in the time domain.

4.5.2 Energy and sub-band allocation

The first solution proposed is simple to implement. However this solution does not exploit the channel diversity. On the other hand, it is desirable to avoid adjacent channel interference in multi-band UWB systems by confining the spectrum of each channel within its prescribed band, while respecting the FCC spectral mask in a power efficient manner. In this section, there is no constraint of adjacent sub-band. The target is to define the minimum bandwidth and minimum bit duration under energy efficiency constraint. The goal of the algorithm is to define the combination of $\{T_b, B\}$ for systems under energy efficiency (β) constraint. The first step of this new algorithm, named Algorithm 3 is to sort the sub-bands in descending order. The number of sub-bands k used is initialed equal to 1, the algorithm calculates the bandwidth and the bit duration so as the value of β is achieved. While the bit duration decreases the number of sub-bands increases, and the algorithm is stopped where the bit time increases and the number of sub-bands increases i.e $T_b(k+1) \geq T_b(k)$. The algorithm gives the minimum time and bandwidth corresponding to energy efficiency β. The algorithm is written as follows

Algorithm 3

```
Input parameters:
Sort the sub-bands in descending order
K = 1 the number of sub-bands
Fix the energy efficiency β
Calculate combination {T_b, B}
while T_b(k+1) < T_b(k) do
    k = k + 1
    calculate T_b(k), B(k)
end while
T_b^* = T_b(k), B^* = B(k)
```

In Fig. 4.17, the energy efficiency β is plotted versus the bit duration. For the same value of energy efficiency, Algorithm 3 gives the minimum bit duration. Then, the new algorithm requires less energy for the same bit-rate.

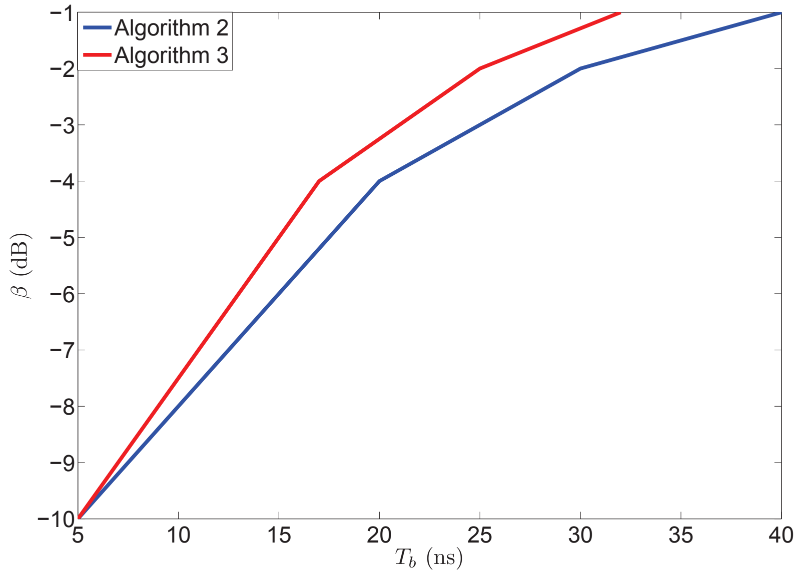

Figure 4.17: Energy efficiency vs the bit duration T_b

4.6 Conclusion

We have investigated various design pulse strategies for communication systems. The choice of the pulse shape is very important to define a new system performance and also to save energy. According to the literature, the second derivative Gaussian pulse is used in the low power environment, or low energy. In this way, we have studied and investigated the system parameters for Gaussian pulses. In this chapter, the choice of the system parameters of Gaussian pulses are proposed to respect the energy efficiency value driven by system design and application requirements. For each system constraint, we can use different schemes and parameters of pulse to spend less energy. This approach will be used as basic approach for resource allocation in wireless networks.

In the second part of this chapter, we have examined the problem of guard time adjustment in UWB communications. We have shown that the use of a guard time adjusted to the current transmission conditions is beneficial in terms of achievable system capacity. We have considered constrained capacity for the guard time designing. A low complexity system and simplified strategy to select the guard time duration is introduced. To this end, the optimization method is proposed. The parameter values for all channel models are provided. Furthermore, we have compared all parameters. Numerical results for typical indoor UWB channels have shown significant gains due to guard time adaptation. These gains come from adjusting the guard time according to the instantaneous channel impulse response.

In the last part of this chapter, we focus on MB UWB communications. A new algorithm for resource allocation is proposed to increase the energy efficiency of those systems. In this chapter, the Gaussian pulse is used for transmission, and its parameters are optimized. In the next chapter, we will focus on others pulses to improve the energy efficiency of UWB systems.

Chapter 5

Pulse design

5.1 Introduction

The usual pulse used with UWB system is the Gaussian monocycle pulse. Unfortunately, the Gaussian monocycle is not a flexible pulse and there is less freedom for energy minimization. In communication systems, we can use other pulses. With the new challenge for green radio, the emerging UWB communication systems need to design a new pulse shape in order to achieve optimal energy consumption. In practical systems, with the new developments in DSP hardware, it has become possible to use any pulse shape for digital data transmission. Motivated by these considerations, this chapter deals with the problem of a UWB pulse design. The main question solved here is how to design a pulse without assuming a particular set of basis signals.

In this chapter, we study various pulses shaping that consume less energy than Gaussian pulse. Three transmitting pulses in UWB communications are proposed. Each pulse provides improvement for energy efficiency. The chapter is organized as follows. Firstly, the pulse is optimized in the case of matched filter receiver. Using Cauchy-Schwarz inequality, the time reversal is obtained for energy minimization. Furthermore, an improvement of time reversal pulse is also provided. Secondly, we do not limit ourselves to matched filter receiver. Our approach is to obtain the best transmitting pulse in the general case. The solution of the new problem is then given in this chapter. The new proposed pulse provides a huge energy gain for UWB communications. We present numerical results of UWB systems with indoor UWB channels that confirm the gains achieved with the proposed pulse.

5.2 Time reversal pulse

In UWB impulse radio, each information symbol is conveyed over basic pulses with one pulse per frame. Each unit-energy pulse has an ultrashort duration at the nanosecond scale. In this chapter, we describe the signal design criteria at the transmitter side. Firstly, we try to find out a better combination of functions using some mathematical method with consideration about tradeoff between the performance and energy consumption.

Recently, various pulses for UWB communications are proposed to improve the system performances. In [126] pulse design under BER constraint is treated. An other pulse is proposed in [127] which suggests a digital finite impulse response filter approach to synthesize UWB pulses filter design techniques by which optimal waveforms that closely match the spectral rank can be obtained efficiently. Otherwise, energy consumption for short-range radios has become an active research area with proliferation of portable electronics [128]. Therefore, our approach is to minimize the energy consumption under SNR constraints. This approach leads to define a new pulse waveform for UWB systems and this pulse is used to minimize the consumed energy.

5.2.1 Pulse design: Cauchy-Schwarz inequality

In this section we propose the pulse that meets the SNR constraint. The SNR ratio is be taken as performance constraint for energy optimization. The ratio of an information signal to the noise associated with observing this signal is a figure of merit that describes the quality of a communication system.

The first target in this section is to find the pulse that maximizes the SNR ratio in the case of matched filter receiver. An alternative to directly minimizing the energy consumption is to define an approximate lower bound of the SNR formula. A sub-optimal solution can be found by applying the Cauchy-Schwarz inequality. Using the communication system introduced in Chapter 2, it is assumed that the waveform of the transmitter pulse is unknown. The CSI is known at the transmitter side and the matched filter is used at the receiver side. The system model is shown in Fig. 5.1. With $f(t)$ the signal at the transmitter side with unknown formula, the mathematical model of the system is written as [61]

$$r(t) = y(t) + \eta(t) \tag{5.1}$$

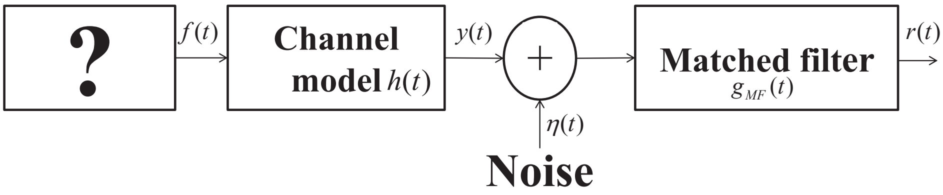

Figure 5.1: System model

where $y(t)$ is the useful signal at the receiver side and $\eta(t)$ is the noise signal. The detailed received signal is

$$r(t) = (f \star g_{MF} \star h)(t) + (\eta \star g_{MF})(t) \tag{5.2}$$

where $g_{MF}(t)$ is the matched filter, and

$$r(t) = \int_{-\infty}^{+\infty} d(\tau)h(t-\tau)d\tau + \int_{-\infty}^{+\infty} \eta(\tau)g_{MF}(t-\tau)d\tau \tag{5.3}$$

where

$$d(t) = (f \star g_{MF})(t) \tag{5.4}$$

The SNR ratio is written as

$$SNR = \frac{|\int d(\tau)h(t-\tau)d\tau|^2}{E[\int\int \eta(\tau)\eta(\tau')g_{MF}(t-\tau)g_{MF}(t-\tau')d\tau d\tau']} \tag{5.5}$$

When there is not inter-symbol interference, the output SNR per bit obtained with the matched filter is

$$SNR = \frac{|\int_{-\infty}^{+\infty} d(\tau)h(t-\tau)|d\tau|^2}{N_0 \int |g_{MF}(t-\tau)|^2 d\tau} \tag{5.6}$$

using the Cauchy-Schwarz inequality the formula (5.6) becomes

$$SNR \leq \frac{\int |d(\tau)|^2 d\tau \int |h(t-\tau)|^2 d\tau}{N_0 \int |g_{MF}(t-\tau)|^2 d\tau} \tag{5.7}$$

$$SNR \leq \frac{\int |f_i(\tau)|^2 d\tau \int |g_{MF}(t-\tau)|^2 d\tau \int |h(t-\tau)|^2 d\tau}{N_0 \int |g_{MF}(t-\tau)|^2 d\tau} \tag{5.8}$$

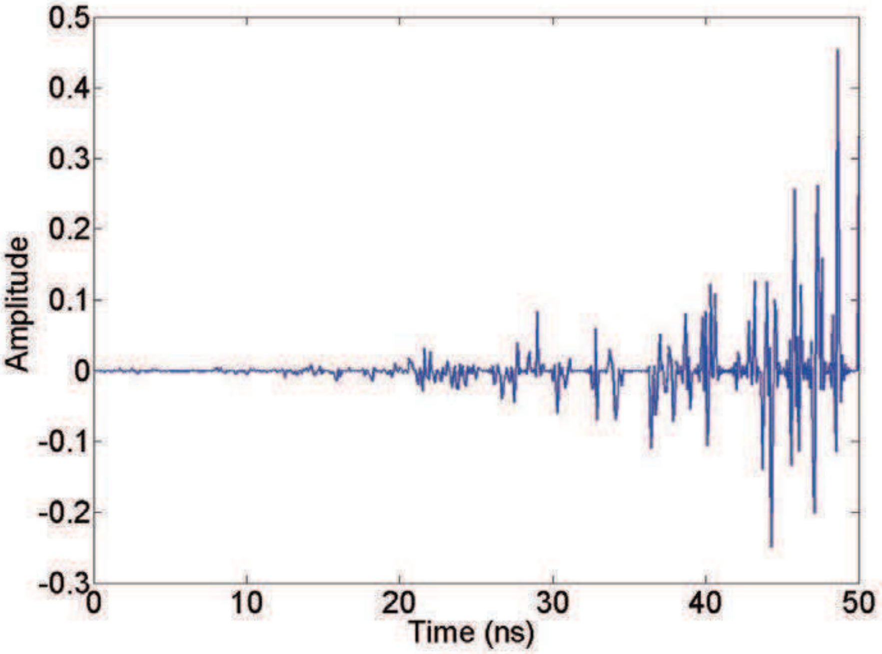

Figure 5.2: Optimal pulse

Finally, the sub-optimum solution is

$$SNR \leq \frac{\int |f_i(\tau)|^2 d\tau \int |h(t-\tau)|^2 d\tau}{N_0} \tag{5.9}$$

The equality will be realized when $f_i(\tau) = kh^*(t-\tau)$ at $t = 0$, then $f_i(\tau) = kh^*(-\tau)$. Then the sub-optimal pulse obtained with Cauchy-Schwarz inequality is the inverse of the channel signal $f_i(\tau) = h^*(-\tau)$. This pulse is optimal in the case of the matched filter without interference inter-symbol and white noise. The pulse in the case of CM1 channel model is plotted in Fig. 5.2. This pulse is exactly the waveform of time reversal signal. Time reversal pulse is increasingly used in wireless communications [129]. The pulse reversal signal transmission is an ideal technique to save energy because of its inherent nature to fully harvest energy from the surrounding environment by exploiting the multi-path propagation, as shown in Fig. 5.2, to re-collect all the signal energy that would have otherwise been lost in most existing communication paradigms. We note that the time reversal signal is obtained by the feedback of the phase and the magnitude parameters of transmitter pulses.

Bandwidth	1 GHz
Bit duration (T_b)	40 ns
Pulse duration	5 ns
Guard time	35 ns
L	1
Channel model	CM1

Table 5.1: System parameters

5.2.2 Comparison between UWB pulse and time reversal pulse

In this section, we present numerical evaluations of monocycle and time reversal pulses in UWB channel. In particular, our attention is focused on performance comparison between both pulses. BER and system capacity performance are plotted versus the E_b/N_0 (energy per bit to noise power spectral density ratio). Perfect synchronization and channel estimation are assumed and the channel transfer function is known at both transmitter and receiver sides. The multi-path channel model of UWB given in Chapter 2 is used. The channel and system parameters are summarized in Table 5.1. The bandwidth and bit duration for both pulses are similar. The same bit energy is used for both pulses. The formula of the system capacity is obtained using the Shannon capacity formula in the case of Gaussian noise and interferences. The system capacity is

$$C = \frac{1}{T_b} \log_2(1 + SINR) \tag{5.10}$$

Let us now compare the performance for both pulses, i.e. monocycle pulse and time reversal pulse. Fig. 5.3 and Fig. 5.4 represent the system capacity and the bit error rate versus E_b/N_0. The time reversal pulse provides the best performances in term of BER and channel capacity for fixed value of E_b/N_0. The gap gain between both pulses is more than 3 dB. In term of energy efficiency, for the same BER, the system with the time reversal pulse needs 50 % of energy less than the system with the monocycle pulse. As shown in Fig. 5.3, a gain factor of 50 % in energy saving is then reached with time reversal pulse. This pulse provides energy gains in communication systems with the same performance. We show through numerical simulations that the time reversal pulse compared to the Gaussian monocycle reveals significant energy reduction. On the other hand, time reversal improves the quality of the received signal.

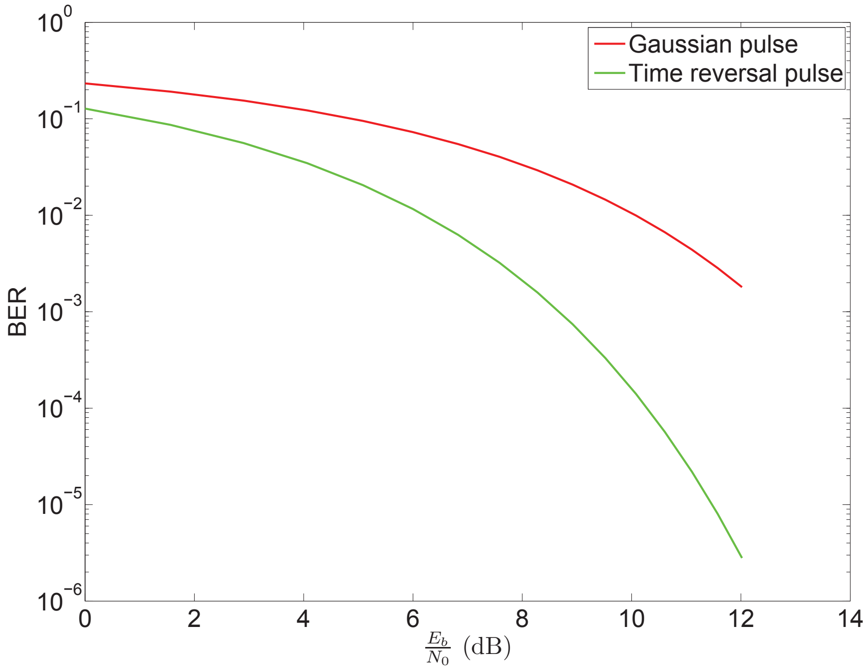

Figure 5.3: BER vs E_b/N_0

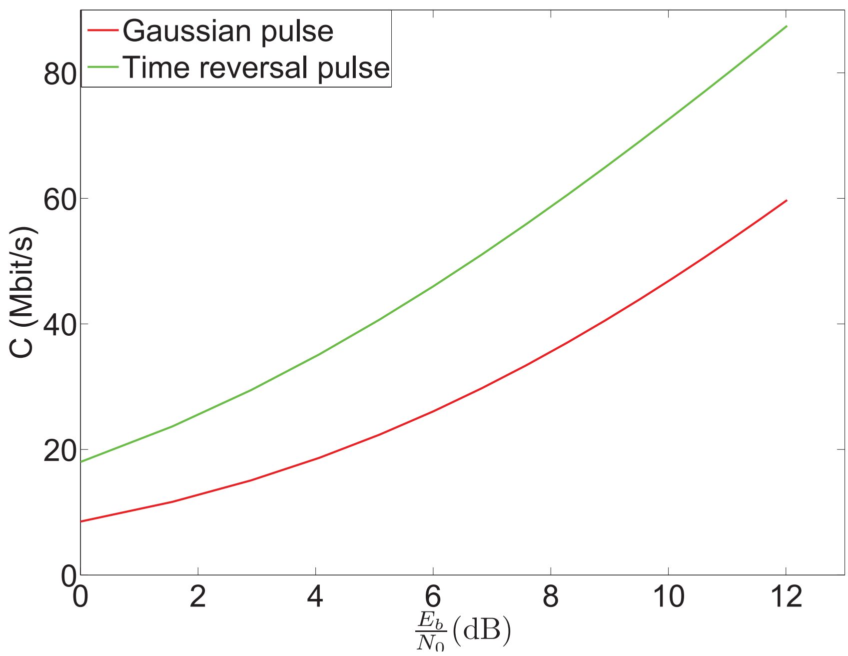

Figure 5.4: System capacity vs E_b/N_0

5.2.3 Pulse without phase estimation

The time reversal pulse saves energy and provides high performance in communication systems. However, this pulse is dependent on the knowledge of CSI at transmitter side. The system with time reversal pulse requires feedback to design the pulse. The system needs to transmit the amplitude and the phase of the channel at transmitter side. Then, in this case we propose a new pulse for communication systems. The proposition is to develop new pulse model for communication systems which offers similar performance to the time reversal pulse. In this section, the analysis is realized in frequency domain.

The received signal without noise of in the frequency domain in the case of time reversal is defined as $G(f) = |A(f)|^2$, where $G_{tx}(f) = |A(f)|exp(j\theta_{ch})$, is the transmitted signal, $H(f) = |A(f)|\exp(-j\theta_{ch})$ is the channel response and the matched filter is defined as $G_{MF}(f) = |A(f)|^2$.

The proposed method is to reduce the number of parameters retransmitted to the transmitter side. The target is to alleviate the feedback. In this case, the system consumes less energy. The same performance as the performance of time reversal pulse is obtained. The new pulse needs to retransmit only the amplitude of the channel response. The transmitted signal is then $G_{tx}(f) = |A(f)|$. In this case, the matched filter becomes $G_{MF} = |A(f)|^2 \exp(j\theta_{ch})$. For this new pulse, the received signal without noise is $G(f) = |A(f)|^2$. The system can achieve the same energy saving compared to the first approach (time reversal pulse) using an easier feedback. Mathematical and numerical results show that the proposed pulse provides the same gains compared to the time reversal pulse. With this new pulse, the system needs less energy and keeps the same performance. The time reversal pulse involves to feedback both magnitude and phase components of the frequency response, whereas only the amplitude component must be feedback with this new pulse.

5.3 Optimal pulse for energy minimization

5.3.1 Problem formulation

In this section, our target is to define the optimal pulse for energy minimization. In [56] the minimum energy required to realize communication system is defined. The time reversal pulse is proposed as the first solution of energy efficiency. To establish a more explicit formulation of energy minimization, we explain here the formulation optimization problem. In this section, we try to find the pulse that needs the lowest energy at the transmitter side to obtain a constant SNR. The solution is not limited to the matched filter receiver and it is formulated in the general case. The received signal, in the single user case, can be written as

$$x(t) = (h \star f)(t) \tag{5.11}$$

where $f(t)$ is the transmitted signal and $h(t)$ is the channel response. The optimization problem for pulse design is formulated as follows

$$\min \quad E_b \quad \text{subject to} \quad \frac{\sum_{i=0}^{N_x-1} \left(\sum_{j=0}^{N-1} f_j h_{i-j} \right)^2}{\sigma^2} = SNR \tag{5.12}$$

The optimization problem (5.12) is solved in the digital domain, where the pulse waveform is

$$f = [f_0, f_1, ..., f_{N-1}] \tag{5.13}$$

and the channel matrix is defined as

$$G = \begin{cases} h_{i-j}, 0 \geq i - j \geq N \\ 0, else \end{cases} \tag{5.14}$$

Thus, the convolution expression of (5.11) is

$$x = G \times f \tag{5.15}$$

Hence, the problem defined in (5.12) is convex, then is directly solvable using the Lagrangian tools. Lagrangian is defined as

$$L = \sum_{i=0}^{N} f_i^2 + \lambda \Big(\sigma^2 SNR - \sum_{i=0}^{N_x-1} (\sum_{j=0}^{N-1} f_j h_{i-j})^2 \Big) \tag{5.16}$$

Taking the square-norm definition, the Lagrangian becomes

$$L = ||f||_2^2 + \lambda \Big(\sigma^2 SNR - ||fG||_2^2 \Big) \tag{5.17}$$

where λ is the Lagrange multiplier. The minimum value of equation is obtained when

$$f = \lambda f G^t G \tag{5.18}$$

The optimal solution f^* is the eigen-vector corresponding to the minimum eigen-value in eigen-function (5.18) and f^* satisfies the constraint of SNR. The resulting design method yields to the pulse that minimizes the energy and satisfies the SNR value.

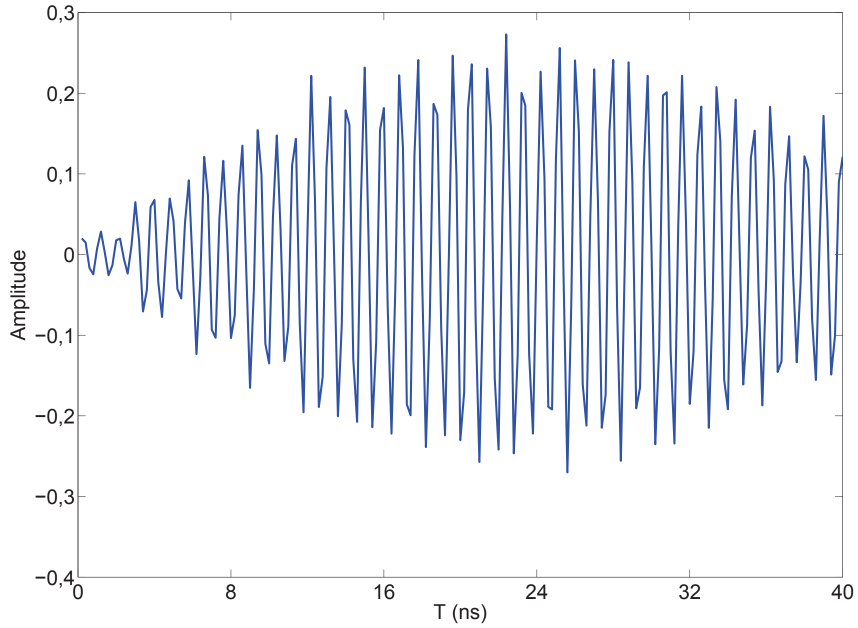

Figure 5.5: Optimal pulse over CM1 channel

5.3.2 Performance evaluation

In this section, we present simulation evaluations of Gaussian and optimal pulse in UWB channel. The evaluation is focused on performance comparison between both pulses. SNR and system capacity performance are plotted versus the energy per bit. Perfect synchronization and channel estimation are assumed and the channel transfer function is known at both transmitter and receiver sides. The multi-path channel CM1 model of IEEE802.15.3a presented in Chapter 2 is used for simulations. The bandwidth and the bit time for both pulses are the same. The same energy is used for both pulses. The formula of the system capacity in (5.10) is used. The Gaussian pulse shape of the UWB signal is a Gaussian waveform with $T_p = 5$ ns and $T_g = 35$ ns. The bit duration of optimal pulse is $T_b = 40$ ns. We assume that the transmitter has the full knowledge of time delays and attenuations of the channel. The optimal pulse for CM1 channel model is presented in Fig. 5.5. Firstly, our attention is focused on SNR comparison between both pulses, i.e Gaussian and optimal pulse. Fig. 5.6 shows the energy of bit versus the SNR ratio. The gap gain factor between both pulses is equal to 7.85 dBJ. In

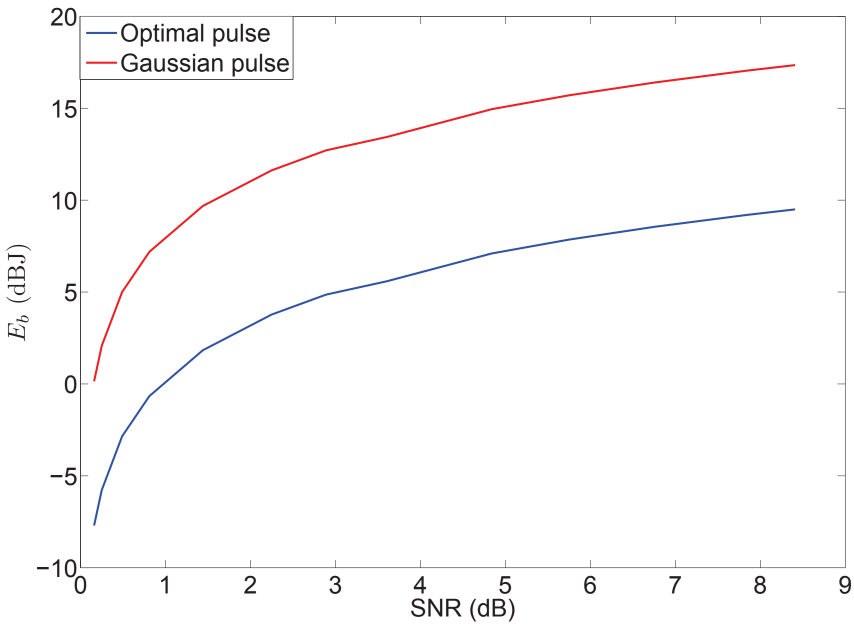

Figure 5.6: SNR vs Energy of bit

term of energy efficiency, for the same SNR, the system with optimal pulse needs 6.1 of energy less than the system with Gaussian pulse. As shown in Fig. 5.6, a gain factor of 6.10 in energy saving is then reached while optimal pulse is used in transmission. This new optimal pulse provides a huge energy gain in communication systems with the same SNR value. For the second step of comparison, we focus on the capacity performance for both pulses. Fig (5.7) shows the capacity versus the $\frac{E_b}{N_0}$ ratio. The optimal pulse provides a huge performance gain compared to the monocyle Gaussian. For the same value of system capacity, the energy gain factor 7.85 dB is reached. This gain is explained by the fact that the new pulse is better adjusted to the current transmission conditions than Gaussian pulse.

5.4 Conclusion

In this chapter, we have examined the problem of designing pulse in UWB communications. According to the literature, the choice of the pulse shape is very important to optimize the system performance and also to save energy. New pulses waveforms have been proposed and defined to save energy. The use of new pulses requires less energy

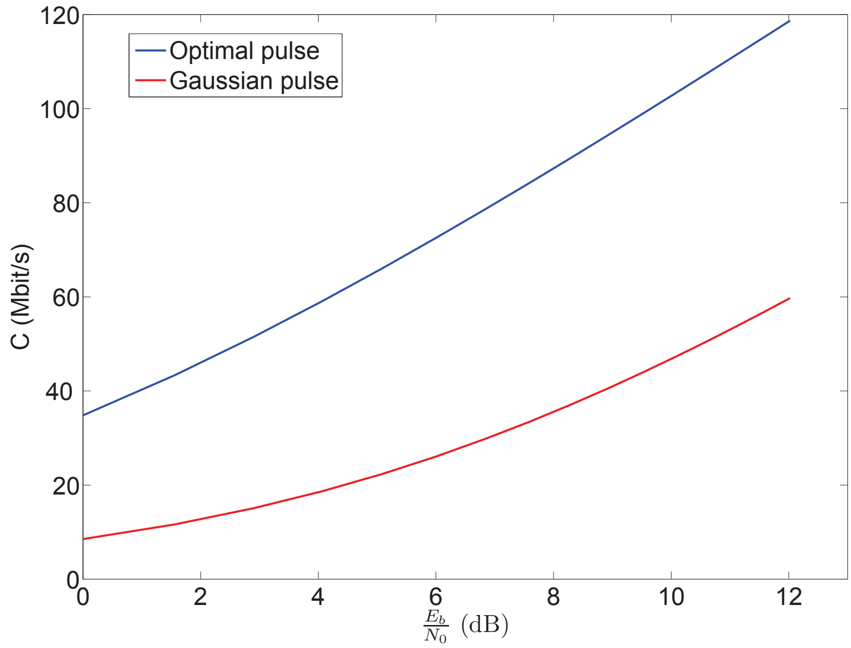

Figure 5.7: System capacity vs $\frac{E_b}{N_0}$

which differs from the conventional Gaussian pulse. In this chapter, we have proposed two pulses. We have shown that the use of a new pulse adjusted to the current transmission conditions is beneficial in terms of energy saving. Numerical results for indoor UWB channels have shown significant gains for energy consumption. These gains come from adaptation of the pulse waveform to the instantaneous channel impulse response. Initially, the time reversal pulse is proposed for UWB communication systems to save energy. Simulation results show that this pulse is attractive in communication systems and energetic gains more than 3 dBJ can be reached in UWB communications with the same performances in term of BER and system capacity. Furthermore, a new pulse is also proposed to reduce the feedback complexity. This new pulse permits the same system performances as the time reversal pulse and reduces the feedback complexity. Secondly, a new optimal pulse in terms of energy consumption is proposed for communication systems. Simulation results show a high significant gain with this optimal pulse. This new pulse is attractive for communication system and energetic gains of 7.85 dBJ can be reached in UWB communications with the same performances.

Conclusion and perspectives

This thesis primarily investigated various resource allocation and pulse design optimization strategies in order to enhance the energy of single carrier and multi-carrier systems, so that they can be efficiently used in future wireless and wired communications. Theoretical studies were performed to lay the fundamentals of energy consumption in communication systems. Several new ideas were presented such as new UWT approach proposed for communication systems aiming at minimizing energy, energy efficiency metric, green resource allocation, system parameters optimization in UWB and new optimal pulses for energy minimization.

The first two chapters of this document have been devoted to the presentation of the context of the study and the specifications of the implemented systems. The first chapter has given us the opportunity to become familiar with the subject of the study. We first presented ICT sector, its impact and importance in modern society. We defined the term and stated that the ICT scope of our study. After, we have emphasized the environmental and energy context of ICT. We presented a general overview of green technologies. These new green technologies attract the attention of both business and research communities. Several statistics of ICT energy consumption were then presented. Recent developments in ICT sector were also highlighted with a description of various trends and solutions working for the enhancement of energy consumption over wireless and wired communications. In the second chapter, WiMAX, PLC and UWB technologies have been described with a focus on the main characteristics of the transmission channels. On the other hand, we presented the principles of the main transmission techniques we are dealing with in this thesis, mainly the OFDM schemes. After reviewing techniques, multi-carrier modulation was described in detail with its parameters. Besides, we described the two main modulation schemes considered for UWB systems: the MB-OFDM and impulse UWB techniques. The MB-OFDM approach is based on the combination of OFDM with a multi-band technique. At the end of the second chapter, we introduced the general problem of resources allocation by presenting the principles, in particular in optimization policies. Then, an overview of energy consumption in WiMAX and PLC systems is provided.

Chapter 3 primarily focused on the energy optimization problem. We have examined the energy consumption problem in a single user context for single carrier and multi-carrier systems. The asymptotic limit of energy consumption for both systems has been provided. This analysis is independent of the technologies constraint. The presented results give the fundamental energy material of a general class with single and parallel channels. A new approach, called UWT, and a new energy efficiency metric have been proposed and defined to save energy. The use of UWT approach provides the lower bound of transmitted energy consumption which differs from the conventional solutions. New allocation algorithms for bits and energy have been developed and formed the basis for multi-carrier systems. In addition, performances of these allocations were compared with those of conventional WiMAX and PLC systems. It was shown that proposed algorithms perform better than existing allocations in terms of energy consumption.

In Chapter 4, we have investigated the aspect of pulse design in UWB communication systems. This chapter was divided in three parts. In the first part, we focused on energy minimization. According to the literature, the second derivative Gaussian pulse is used in the low power environment, or low energy. In this way, we studied and investigated the system parameters for monocycle Gaussian pulse. The main objective of this study was to obtain the optimal system parameters for a given target energy efficiency. This study also offers a wide variety of combination system parameters that can be chosen depending on the desired system constraints. Chapter 4 introduced an entirely new way for system parameters, where energy consumption of the system is minimized to enhance the system performances. The second part of Chapter 4 extended the UWB study to capacity maximization. A theoretical study was performed for UWB systems to maximize the capacity and energy distribution. We have shown that the use of a guard time adjusted to the current transmission conditions is beneficial in terms of achievable system capacity. We have considered constrained capacity for the guard time designing. A low complexity system and simplified parameter to select the guard time is introduced. To this end, the optimization method is proposed.

The parameter values for all channel models are provided. Furthermore, we have compared all parameters. Numerical results for typical indoor UWB channels have shown significant gains due to guard time adaptation. These gains come from adjusting the guard time according to the instantaneous channel impulse response. In the last part of this chapter, we focused on MB-UWB communications. A new algorithm for resource allocation is proposed to increase the energy efficiency of the system. Bit and energy algorithms were also discussed in combination of simple approach and simulation results were presented.

In Chapter 5, we extended the study of pulse design and energy optimization for UWB systems. In this chapter, we introduced energy optimization taking into account the SNR constraint. Two pulses were proposed, one for time reversal and the other for optimal energy systems in the context of UWB communications. It was shown that proposed pulses provide significant gain for UWB communications. They give better system capacity performance for low values of bit energy.

Many prospects can be listed for future works based on this thesis:

- The work carried out in this thesis has focused on energy consumption for communication systems without taking into account the energy consumption for practical systems. However, this work may be extended to a practical system taking into account the system energy consumption.

- The resource allocation algorithms focus only on the physical layer. An interesting future work would be to implement and test these algorithms in the final OFDM systems. Besides, these algorithms could be combined within enhanced cross layer mechanisms in order to improve the system performance, while respecting the QoS requirements and constraints provided by the MAC layer. Thus, dynamic cross-layer spectrum allocation for high data rate systems could be developed without notably increasing the system complexity. Furthermore, the resource allocation algorithms with multi-user scenario should be developed.

- The resource allocation schemes may be extended to the case of imperfect CSI consideration.

- In this thesis, two degrees of freedom (time and frequency) have been exploited. In this way, an additional degree of freedom for communication systems can improve the energy efficiency. Thus, the exploitation of the space-time-frequency domain for high data rate systems could be developed without notably increasing the system complexity.

- The proposed pulse design optimization takes into account the SNR value in order to enhance the energy efficiency. To develop a new pulse taking into account other performance criteria as system capacity will lead to the propose of a new pulses for UWB communications.

Appendix A

The target of this calculation is to find the solution of the formula has a form as

$$b = (2^{1/ax} - 1)ax \tag{5.19}$$

$$b = (\frac{1}{2^{-1/ax}} - 1)ax \tag{5.20}$$

multiplying and dividing by $\log 2$

$$b = (\frac{\log 2}{2^{-1/ax}} - \log 2)\frac{ax}{\log 2} \tag{5.21}$$

$$\frac{\log 2}{2^{-1/ax}} = (\frac{b \log 2}{ax} + \log 2) \tag{5.22}$$

$$\log 2 = (\frac{b \log 2}{ax} + \log 2)2^{-1/ax} \tag{5.23}$$

$$\frac{\log 2}{b} = (\frac{\log 2}{ax} + \frac{\log 2}{b}) \exp(-\frac{\log 2}{ax}) \tag{5.24}$$

$$\exp(-\frac{\log 2}{b})\frac{\log 2}{b} = (\frac{\log 2}{ax} + \frac{\log 2}{b}) \exp(-\frac{\log 2}{ax}) \exp(-\frac{\log 2}{b}) \tag{5.25}$$

$$\exp(-\frac{\log 2}{b})\frac{\log 2}{b} = (\frac{\log 2}{ax} + \frac{\log 2}{b}) \exp(-(\frac{\log 2}{ax} + \frac{\log 2}{b})) \tag{5.26}$$

with Lambert function W defined as

$$x = y \exp(y) \Rightarrow y = W(x) \tag{5.27}$$

$$-(\frac{\log 2}{ax} + \frac{log2}{b}) = W\big(- \exp(-\frac{-\log 2}{b})\frac{\log 2}{b}\big) \tag{5.28}$$

$$\frac{-\log 2}{ax} = W(-\exp(-\frac{log2}{b})\frac{\log 2}{b}) + \frac{\log 2}{b} \tag{5.29}$$

$$ax = -\frac{\log 2}{W\big(-\exp(-\frac{log2}{b})\frac{\log 2}{b}\big) + \frac{\log 2}{b}} \tag{5.30}$$

$$ax = -\frac{b\log 2}{bW\big(-\exp(-\frac{log2}{b})\frac{\log 2}{b}\big) + \log 2} \tag{5.31}$$

$$x = -\frac{b\log 2}{a\big[bW\big(-\exp(-\frac{log2}{b})\frac{\log 2}{b}\big) + \log 2\big]} \tag{5.32}$$

Appendix B

Capacity

Let us first consider BPSK signaling, for which we have the channel model

$$Y = \sqrt{E_s}X + N,\ X \in \{-1, +1\},\ N \sim \mathcal{N}(0, \sigma^2) \tag{5.33}$$

that the mutual information I(X,Y), subject to the constraint of BPSK signaling, is maximized for equiprobable signaling. Let us now compute the mutual information I(X,Y) as a function of the signal power E_s and the noise power σ^2. We first show that, as with the capacity without an input alphabet constraint, the capacity for BPSK also depends on these parameters only through their ratio, the SNR E_s/σ^2. To show this, replace Y by Y/σ to get the model

$$Y = \sqrt{SNR}\,X + N,\ N \sim \mathcal{N}(0, \sigma^2) \tag{5.34}$$

For notational simplicity, set $A = \sqrt{SNR}$. We have

$$p(Y| + 1) = \frac{1}{\sqrt{2\pi}} \exp\left(-(Y - A)^2/2\right) \tag{5.35}$$

$$p(Y| - 1) = \frac{1}{\sqrt{2\pi}} \exp\left(-(Y + A)^2/2\right) \tag{5.36}$$

and

$$p(Y) = \frac{1}{2}p(Y| + 1) + \frac{1}{2}p(Y| - 1) \tag{5.37}$$

$$p(Y) = \frac{1}{2}\frac{1}{\sqrt{2\pi}}\sum_{s=1}^{2}\exp\left(-(Y+b_sA)^2/2\right) \tag{5.38}$$

where $b_s = \{-1, 1\}$

We can now compute

$$I(X,Y) = h(Y) - h(Y,X) \tag{5.39}$$

As on [124], we can show that $h(Y|X) = h(Z) = 1/2\log_2(2\pi e)$. We can now compute

$$h(Y) = -\int \log_2(p(Y))p(Y) \tag{5.40}$$

by numerical integration, plugging in (5.36). An alternative approach, which is particularly useful for more complicated constellations and channel models, is to use Monte Carlo integration (i.e., simulation-based empirical averaging) for computing the expectation $h(Y) = -E[\log_2 p(Y)]$. For this method, we generate i.i.d. samples Y_i using the model (5.34), and then use the estimate

$$h = -\frac{1}{n}\sum_{1}^{n}\log_2 p(Y_i) \tag{5.41}$$

then the capacity

$$C = -E[\log_2 p(Y)] - 1/2\log_2(2\pi e) \tag{5.42}$$

$$C = -E[\log_2 \frac{1}{2}\frac{1}{\sqrt{2\pi}}\sum_{i=1}^{2}\exp\left(-(Y+b_iA)^2/2\right)] - 1/2\log_2(2\pi e) \tag{5.43}$$

Capacity with interference

- One bit of interference

$$\begin{aligned} p(Y) = {} & \frac{1}{4}p(Y|(+1,a_1)) + \frac{1}{4}p(Y|(+1,-a_1)) \\ & + \frac{1}{4}p(Y|(-1,-a_1)) + \frac{1}{4}p(Y|(-1,a_1)) \end{aligned} \tag{5.44}$$

where a_1 is the amplitude interference.

$$p(Y) = \frac{1}{4}\frac{1}{\sqrt{2\pi}}\Big(\exp -\frac{(Y-A+a_1)^2}{2} + \exp -\frac{(Y-A-a_1)^2}{2} + \exp -\frac{(Y+A+a_1)^2}{2} + \exp -\frac{(Y+A-a_1)^2}{2}\Big) \tag{5.45}$$

then

$$h(Y) = -E\Big[\log_2\Big(\frac{1}{4}\frac{1}{\sqrt{2\pi}}(\exp -\frac{(Y-A+a_1)^2}{2} + \exp -\frac{(Y-A-a_1)^2}{2} + \exp -\frac{(Y+A+a_1)^2}{2} + \exp -\frac{(Y+A-a_1)^2}{2})\Big)\Big] \tag{5.46}$$

- Two bits of interference

$$\begin{aligned} p(Y) = {} & \frac{1}{8}p(Y|(+1,a_1,a_2)) + \frac{1}{8}p(Y|(+1,a_1,-a_2)) \\ & + \frac{1}{8}p(Y|(+1,-a_1,-a_2)) + \frac{1}{8}p(Y|(+1,-a_1,a_2)) \\ & + \frac{1}{8}p(Y|(-1,a_1,a_2)) + \frac{1}{8}p(Y|(-1,a_1,-a_2)) \\ & + \frac{1}{8}p(Y|(-1,-a_1,-a_2)) + \frac{1}{8}p(Y|(-1,-a_1,a_2)) \end{aligned} \tag{5.47}$$

$$\begin{aligned} p(Y) = \frac{1}{8}\frac{1}{\sqrt{2\pi}}\Big(& \exp -\frac{(Y-A+a_1+a_2)^2}{2} + \exp -\frac{(Y-A+a_1-a_2)^2}{2} \\ & + \exp -\frac{(Y-A-a_1-a_2)^2}{2} + \exp -\frac{(Y-A-a_1+a_2)^2}{2} \\ & + \exp -\frac{(Y+A+a_1+a_2)^2}{2} + \exp -\frac{(Y+A+a_1-a_2)^2}{2} \\ & + \exp -\frac{(Y+A-a_1+a_2)^2}{2} + \exp -\frac{(Y+A-a_1-a_2)^2}{2}\Big) \end{aligned} \tag{5.48}$$

then

$$\begin{aligned} h(Y) = -E\Big[\log_2\Big(\frac{1}{8}\frac{1}{\sqrt{2\pi}}(& \exp -\frac{(Y-A+a_1+a_2)^2}{2} + \exp -\frac{(Y-A+a_1-a_2)^2}{2} \\ & + \exp -\frac{(Y-A-a_1-a_2)^2}{2} + \exp -\frac{(Y-A-a_1+a_2)^2}{2} \\ & + \exp -\frac{(Y+A+a_1+a_2)^2}{2} + \exp -\frac{(Y+A+a_1-a_2)^2}{2} \\ & + \exp -\frac{(Y+A-a_1+a_2)^2}{2} + \exp -\frac{(Y+A-a_1-a_2)^2}{2})\Big)\Big] \end{aligned} \tag{5.49}$$

$$h(Y) = -E\Big[\log_2\Big(\frac{1}{2^{n+1}}\frac{1}{\sqrt{2\pi}}\sum_{s=1}^{2}\sum_{i=1}^{2^n}\exp(-\frac{(y-b_sA+\sum_{j=1}^{n}a_j\alpha_{j,i})^2}{2})\Big)\Big] \quad (5.50)$$

the capacity for interference

$$C = -E\Big[\log_2\Big(\frac{1}{2^{n+1}}\frac{1}{\sqrt{2\pi}}\sum_{s=1}^{2}\sum_{i=1}^{2^n}\exp(-\frac{(y-b_sA+\sum_{j=1}^{n}a_j\alpha_{j,i})^2}{2})\Big)\Big] - 1/2\log_2(2\pi e) \quad (5.51)$$

where n is the number of bit interference, a_j is the interference amplitude of j bit, $\alpha_{j,i}$ is the matrix of possible case of interference with a dimension $\{n, 2^n\}$ and $b_s = \{-1, 1\}$. As example for $n = 2$:

$$\alpha_{j,i} = \begin{pmatrix} +1 & -1 \\ +1 & +1 \\ -1 & +1 \\ -1 & -1 \end{pmatrix} \quad (5.52)$$

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