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前瞻性行動無線都會網路之設計與性能評估
Design and Performance Evaluation of an Advanced Mobile WiMAX Network

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執行單位：國立交通大學電信工程研究所

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中文摘要

行動無線都會網路現在世界上正蓬勃發展,因此對系統的效能要求也越來越高。行動無線都會網路系統可提供無線高速行動應用,但也因此面對嚴重的多路徑干擾效應而減低系統的效能。故處理多路徑干擾效應的解決方案目前正被行動無線都會網路研究論壇所注意。在本計畫中,我們設計了一套改良式的行動無線都會網路系統架構,運用現行的技術,如正交分頻多重進接/分碼多重進接系統技術(OFDMA/CDMA)、多路徑干擾消除技術(MPIC)、低密度同位檢查碼(LDPC code)、渦輪等化(turbo equalization)等來改善行動無線都會網路系統的效能。我們使用計算機模擬以評估所設計的系統與傳統行動無線都會網路系統的性能;我們發現,所設計的系統相對於傳統系統的效能有相當大的改善程度。我們提供以正交分頻多重進接/分碼多重進接系統技術為基礎的行動無線都會網路系統,在傳收端應用展頻技術並在接收端應用多路徑干擾消除技術,不但可以減低多路徑干擾的效應,而且可以提供更好的系統效能。

此外,從蜂巢式系統的模擬結果,我們可以觀察出在滿載時(full load),系統效能都是 CDMA 比 OFDM 來的好,特別是當我們在基地台使用有方向性的接收天線,可有效的濾掉其他細胞來的干擾(intra-cell interference),以降低錯誤率(error rate)。

雖然 OFDM 本身內部的子載波彼此正交,不會互相干擾;而 CDMA 有 MAI 的問題,但是使用 PEC 等化器可以有效消除部分的 MAI 問題。尤其是當負載降低的時候,在 4-path 的情形,CDMA 的系統效能比 OFDM 來得佳。

末了,我們提出了一個多細胞 OFDMA 調變在蜂巢式系統間干擾消除(inter-cell interference mitigation, ICIM)的方法,我們特別針對下行(downlink, DL)傳輸作討論。基本想法是於部分頻率再利用(Partial frequency reuse, PFR)和軟性換手(Soft handover, SH)間動態地作選擇,以提供蜂巢式系統中邊緣用戶較好的訊號品質。模擬結果顯示,與標準的 PFR 相比,該方法有助於改善邊緣用戶的鏈結品質(link quality)和鏈結的頻譜效率(link spectral efficiency)。

關鍵詞:無線都會網路系統、正交分頻多重進接系統、分碼多重進接系統、多路徑干擾消除、低密度同位檢查碼、渦輪等化、蜂巢式系統

英文摘要

Since the mobile WiMAX is under developement rigorously in the world, there are much more demands for system performance than before. In the mobile WiMAX, it can provide high speed mobile applications, but may also suffer from serious multipath effects which will degrade the system performance. Thus, the solutions to the multipath effect are being highlighted by the WiMAX research forum.

In this project, we design a modified architecture of the mobile WiMAX system. We use several existing techniques, such as OFDM/CDMA, multipath interference cancellation (MPIC) technique, low density parity check code (LDPC code), and turbo equalization to improve the mobile WiMAX system performance. Computer simulations are conducted to assess the performance of the proposed system and that of the traditional mobile WiMAX system. We found that there’s a great improvement in the performance for our system over the traditional one.We provide a OFDM/CDMA-based mobile WiMAX system utilizing the spreading technique and the MPIC technique in the tranceiver that can not only reduce the multipath effect but provide the better system performance.

From the simulation results of the cellular system, one can observe that the system performance of CDMA is always better than that of OFDM under full loading scenarios. In particular, the interferences from other cells can be effectively diminished to reduce the error rate when the directional antennas are applied in the base station.

It’s known that there’s no inter-carrier interferences for OFDM due to mutual orthogonality between each subcarrier whereas MAI arises in CDMA system which causes the degradation of the system performance. However, PEC equalizers could efficiently alleviate such problems, especially for light loading systems. For example, CDMA systems outperforms OFDM under four-path channel condition.

Finally, we proposed an inter-cell interference mitigation scheme for a multi-cell OFDMA system, and in particular we focus on downlink transmission. The basic idea of the proposed scheme is to dynamically choose between a partial frequency reuse scheme (with reuse factor 3) and a soft handover scheme to provide better signal quality for cell edge users. Our simulation results show that ,as compared with standard partial frequency reuse scheme, the proposed scheme helps to improve the link quality and link spectral efficiency of cell edge users.

Keywords: mobile WiMAX system, OFDMA, CDMA, multipath interference cancellation, low density parity check code, turbo equalization, cellular system

目錄

第零章 研究目的

IEEE 802 針對不同的環境制訂了不同的無線通訊標準，如應用於無線區域網路(WLAN) IEEE802.11標準，無線個人區域網路(PAN) IEEE 802.15 標準，而IEEE802.16[B1]則為無線都會區域網路標準。其工作頻率介於2～66 GHz 之間，以提供寬頻無線接取。此外IEEE 802.16 標準根據系統是否支援移動特性分為固定寬頻無線接取（Fixed Broadband Wireless Access）如 IEEE 802.16（工作頻率為10～66 GHz），IEEE 802.16a （工作頻率為2～11 GHz），IEEE 802.16c（工作頻率為10～66 GHz）及行動寬頻無線接取（Mobile Broadband Wireless Access）如 IEEE 802.16e（工作頻率為 2～6 GHz)接取方式。IEEE 802.16d (或稱為IEEE 802.16-2004)則是結合前述的802.16、802.16a、802.16c 的標準作增補與修訂，應用於工作頻率為2～11GHz的NLOS（non line-of- sight）及10～66GHz的LOS（line-of-sight）傳輸。802.16e(或稱為IEEE 802.16-2005)為IEEE 802.16d的延伸，可支援車速約120 km/h的行動通訊。

802.16 可支援TDD 與FDD兩種雙工模式，並有三種PHY技術分別為單一載波（SC），OFDM（256點）及OFDMA（可調整最大為2048點），其中，工作頻率10～66GHz 固定寬頻無線接取系統主要採用單一載波技術，工作頻率2～11GHz系統則採用OFDM 與OFDMA技術。相較於802.16d，802.16e的PHY對於OFDMA技術更進一步延伸。在802.16d中，訂定了2048點OFDMA的技術，而在802.16e中則可彈性支援2048，1024，512，128 點以應用於不同環境的不同頻寬，因此又稱其為SOFDMA (Scalable OFDMA)系統架構。

WiMAX 聯盟目前致力於發展基於 IEEE 802.16e 行動寬頻無線接取，並稱其為 Mobile WiMAX。 Mobile WiMAX 採用OFDMA技術以提高在多路徑NLOS環境下的系統效能。且應用了SOFDMA (Scalable OFDMA)，提供了OFDMA系統於可變頻寬（1.25 MHz~20 MHz）以適用於不同傳輸環境。Mobile WiMAX 與眾不同的特性有以下幾點：

- 高資料傳輸量（High Data Rate）
- 服務品質（QoS）
- 可調性 (Scalability)
- 安全性 (Security)
- 行動力 (Mobility)

Mobile WiMAX 採用部分IEEE 802.16e OFDMA 的規範。OFDMA是基於OFDM 調變，但不同於OFDM系統時間與頻率的資源都給特定的個別使用者，OFDMA 則是將OFDM調變後子載波（subcarrier）分組成數個子通道（subchannel）並利用多重接取將多個使用者多工至下行不同子通道（downlink subchannel）及上行不同子通道（uplink subchannel）。因此OFDMA 符元結構上亦與OFDM系統相同，包含有資料載波（Data carrier,傳輸資料用），領航載波(Pilot carrier)，及零值載波（Null carrier）。下圖0-1為包含子通道分工化的OFDMA 符元結構示意圖。

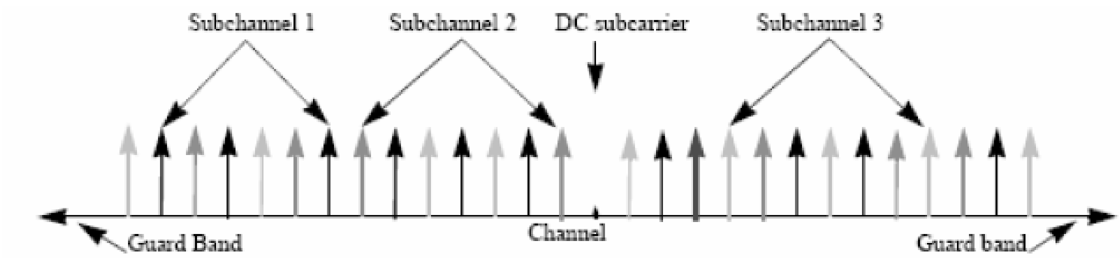

圖0-1 **OFDMA**符元結構示意圖

子載波構成子通道的排列方式分為分集與連續兩種。分集排列是以子載波隨意組成子通道，包括DL FUSC (Fully Used Sub-Carrier), DL PUSC (Partially Used Sub -Carrier) 和UL PUSC，而連續排列則是指以一群連續子載波組成子通道，包括DL AMC（Adaptive Modulation and Coding） 和UL AMC。SOFDMA中的可調性則是指以固定子載波頻率間隔10.94 kHz，調整FFT 點數來調整頻寬。SOFDMA 的可調性相關於系統參數列於表0-1。

參數	參數值			
系統通道頻寬(MHz)	1.25	5	10	20
取樣頻率 （MHz）	1.4	5.6	11.2	22.4
FFT 點數（N_{FFT}）	128	512	1024	2048
子通道個數	2	8	16	32
子載波頻率間隔	10.94 kHz			
可用符元時間（T_b=1/f）	91.4 usec			
護衛時間(T_g=T_b/8)	11.4 usec			
OFDMA 符元時間	102.9 usec			

表0-1 **SOFDMA** 的可調性系統參數表

在Frame structure 方面 雖然802.16e 同時訂有TDD 及全雙工或半雙工FDD模式，但Mobile WiMAX 只選用TDD的模式為認證系統。

在通道編碼方面，流程圖如下圖0-2所示，由隨機發射器（Randomizer），錯誤更正(FEC)，位元交錯器(Bit Interleaver)，反覆編碼（Repetition）及調變器(Modulation)組成。

圖0-2 通道編碼流程圖

不論是DL或者UL的資料都需使用隨機發射器（Randomizer）。傳輸資料先經過由PRBS產生器，如圖0-3所示，所產生的PN序列將由虛擬隨機序列產生，經過隨機化的位元將再經錯誤更正碼編碼，在802.16e中錯誤更正碼的選擇有迴旋碼

(Convolutional Coding)，區塊渦輪碼（BlockTurbo Coding），迴旋渦輪碼（Convolutional Turbo Coding），及低密度同位檢查碼（LDPC）可選擇。目前Mobile WiMAX 選擇的是Tail Biting 的迴旋碼，其餘編碼方式設定為選擇性。
表0-2為Mobile WiMAX DL 與UL 可用的通道編碼，包含碼率及調變方式總結表。
表0-3為802.16e通道編碼碼率總結表。

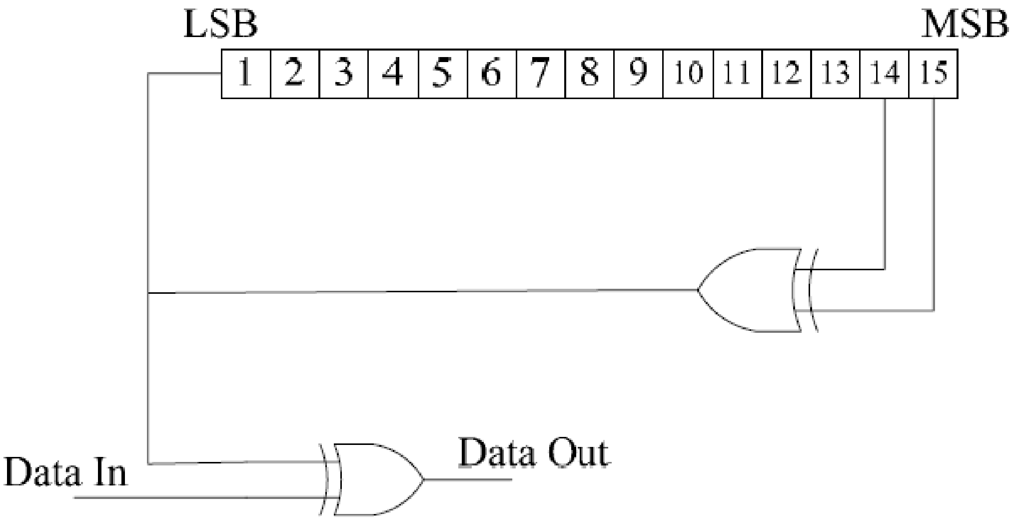

圖0-3 **PRBS** 產生器

		下行（DL）	上行（UL）
調變		QPSK，16QAM，64QAM	QPSK，16QAM，64QAM
碼率	迴旋碼(CC)	1/2,2/3,3/4	1/2,2/3,3/4
	迴旋渦輪碼(CTC)	3/4 （16QAM） 1/2 （64 QAM）	3/4 （16QAM） 1/2 （64 QAM）
	反覆編碼（Repetition）	x2 x4 x6 (QPSK)	x2 x4 x6 (QPSK)

表0-2 **Mobile WiMAX** 選用於**DL** 與**UL**的通道編碼，含碼率，調變總結表

	碼率
迴旋碼(CC)	1/2, 2/3,3/4
區塊渦輪碼（BTC）	1/2,3/4,
迴旋渦輪碼(CTC)	3/4 (16 QAM) 1/2 (64 QAM)
低密度同位檢查碼（LDPC）	1/2, 2/3,3/4,5/6

表0-3 **802.16e**通道編碼碼率總結表

第一章 研究方法

本計畫第一部份的主要研究為設計一套具有OFDM/CDMA規格與多路徑干擾消除之新型WiMAX系統，因為OFDM/CDMA規格與多路徑干擾消除的技術已被視為未來WiMAX發展的大方向之一，因此我們針對此一方向作探討，研究方法可參照圖1-1的架構，我們根據WiMAX的特性加入一組具彈性調整及正交特性的華氏碼作頻域展頻之用，將每個OFDMA的子載波能量分散到區域碼塊中的全部子載波，如此訊號在空間中傳遞將因為展頻增益，而有更強的抗雜訊能力。

本計畫的研究方法，從仔細了解WiMAX領域相關技術與標準制定之詳細內容開始，運用研究的資料內容開始設計一套符合現行WiMAX標準之準系統，並進行效能分析，以作為本計畫效能比較之參考標準。準系統的架構為設計典型WiMAX傳送端與接收端二部份，傳送端的部份將依循WiMAX forum之標準制定設計，接收端的部份視系統效能作最佳化設計，其中包括編碼與解碼器部份，針對里得-所羅門碼(Reed Solomon codes)，迴旋碼(Turbo codes)，LDPC碼作深入研究。設計好準系統之後，接著設計一套如之前所述，具備OFDM/CDMA規格與多路徑干擾消除的技術之新型WiMAX架構，設計架構如圖1-1，圖1-2與圖1-3所示，在傳送端方面，我們加入華氏碼於不同的符元區塊中(依系統要求選擇適當之華氏碼組合)，作為頻域展頻之效果，由於領航載波有其特別通道估計的用途，因此我們只針對資料載波的部份作展頻的動作。華氏碼的長度一般都是以二的n次方為組合，為將華氏碼運用於資料的載波展頻，資料載波將予以切割分組並匹配適合長度的華氏碼，然後予以多工處理。除此之外，我們對LDPC編碼器作進一步的探討，以獲得更好的編碼方式。符元交錯器也是影響系統效能的一個課題，我們研究分析標準內交錯器之特性。在接收端方面，我們加入部份等化器與多路徑干擾消除模組，部份等化器的主要作用，在於依據通道特性的不同，以適合的參數調整等化器，將大部份衰變通道效應的干擾消除。而多路徑干擾消除模組的主要作用，在於依照前一級部份等化器或前一次多路徑干擾消除運算所估計出不同路徑的訊號，利用最大比合併(Maximum Ratio Combining)的能量匯集方法，整合所有路徑之訊號，如此訊號的估計可以更加準確，利用多次多路徑干擾消除模組的運算，系統可以估計的正確性將會隨著運算次數而更加提升。

多路徑干擾消除模組的詳細運作如圖1-3所示，其中包括路徑訊號解析，解展頻運算，最大比合併，訊號重建(再展頻運算，通道訊號重建等)，有了展頻，解展頻的運算，系統可獲得展頻增益而提升性能。接收端還會包括LDPC解碼器之設計，LDPC解碼器的設計是一項研究的重要課題，設計好的解碼器可以讓整體系統效能有更佳的運作狀態。

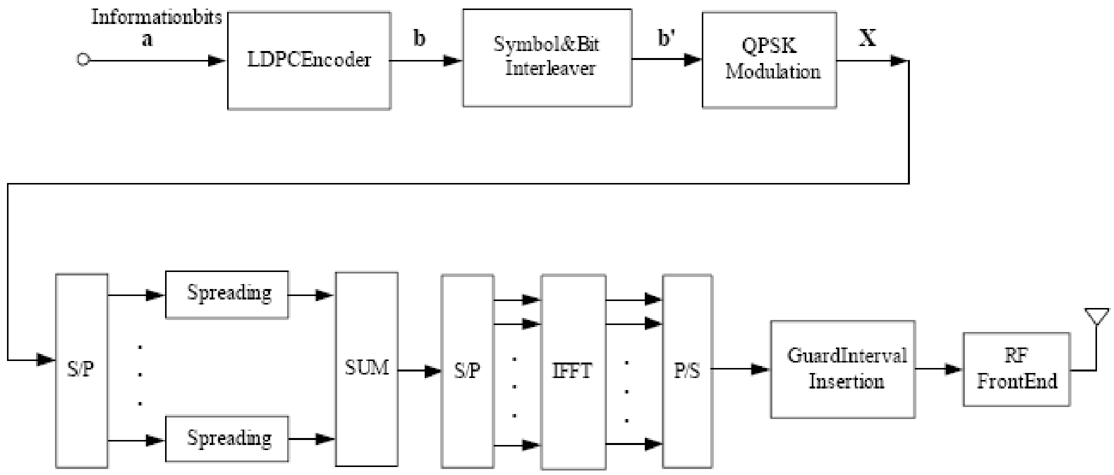

圖1-1 結合多重編碼改良後傳送端架構圖

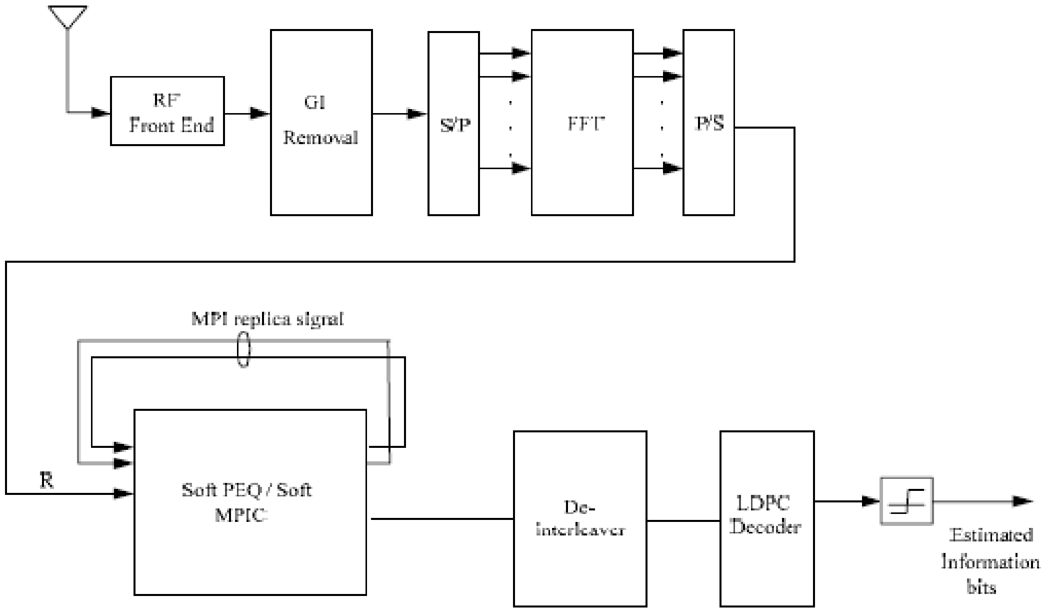

圖1-2結合多重編碼改良後接收端架構圖

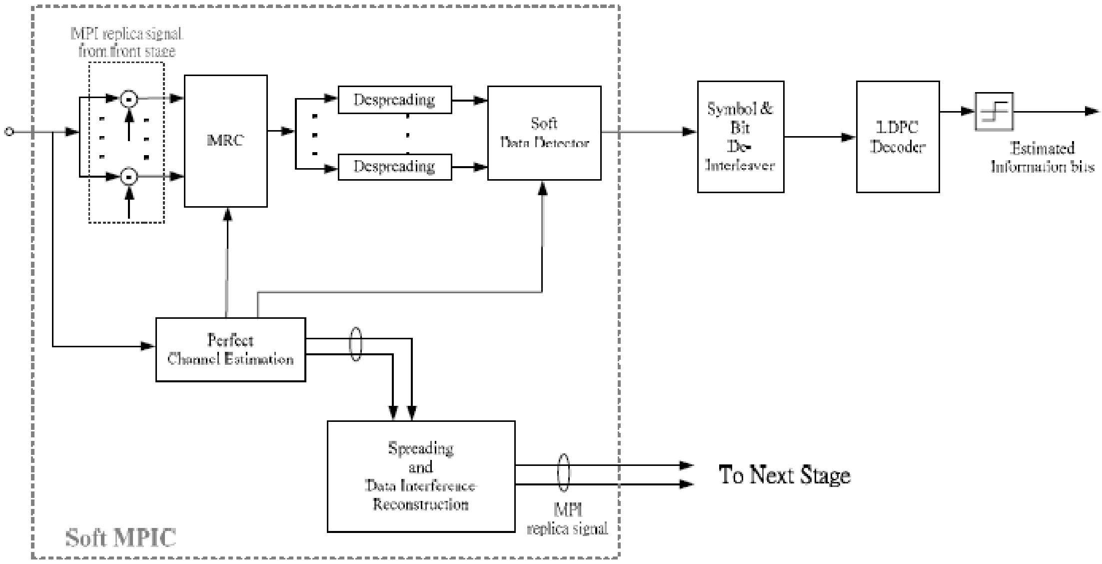

圖1-3 結合多重編碼改良後接收端多路徑干擾消除模組架構圖

本計畫的第二部份以第一部份為基礎作更進一步的研究設計，主要重點放在接收機的設計上面。我們針對軟式資訊數學運算遞迴運算的概念，使其運用在接收機訊號處理。由理論可知，當LDPC的解碼有多次遞迴運算時，將可以提升解碼的正確性，由於LDPC碼的運算是使用軟式訊號，因此若要讓LDPC碼加入整個系統的大遞迴運算，除了LDPC模組本身需要使用軟式訊號，整個接收機的其他運算也需要有相對的訊號轉換機制，因此了解軟式資訊處理的數學理論及選擇適合的軟式資訊轉換機制也是個研究課題，我們會對LDPC軟式資訊數學這一部份做研究，以設計一個適合整體系統架構的運算機制。

設計的概念如圖1-4，圖1-5與圖1-6所示，我們研究LDPC的軟式位元轉換，利用對數相似比運算(Log-likelihood ratio)計算出訊號的內部資訊(intrinsic information)，內部資訊透過LDPC運算，可以計算出通道提供訊息的外部資訊(extrinsic information)，當先前內部資訊扣除LDPC運算的外部資訊之後，會形成一個新的資料類型，而構成系統新輸入的內部資訊，透過軟式資訊數學轉換，可以形成軟位元提供多路徑干擾消除運算模組來重建更具可靠性的多路徑訊號，這重建的訊號處理將包括訊號再展頻，通道效應影響及LDPC再編碼處理運算。透過LDPC碼內部遞迴及整體系統外部遞迴的效應，整個接收訊號的正確性便可提升。我們分析與比較所設計的系統與現行WiMAX forum所訂之規格的效能。

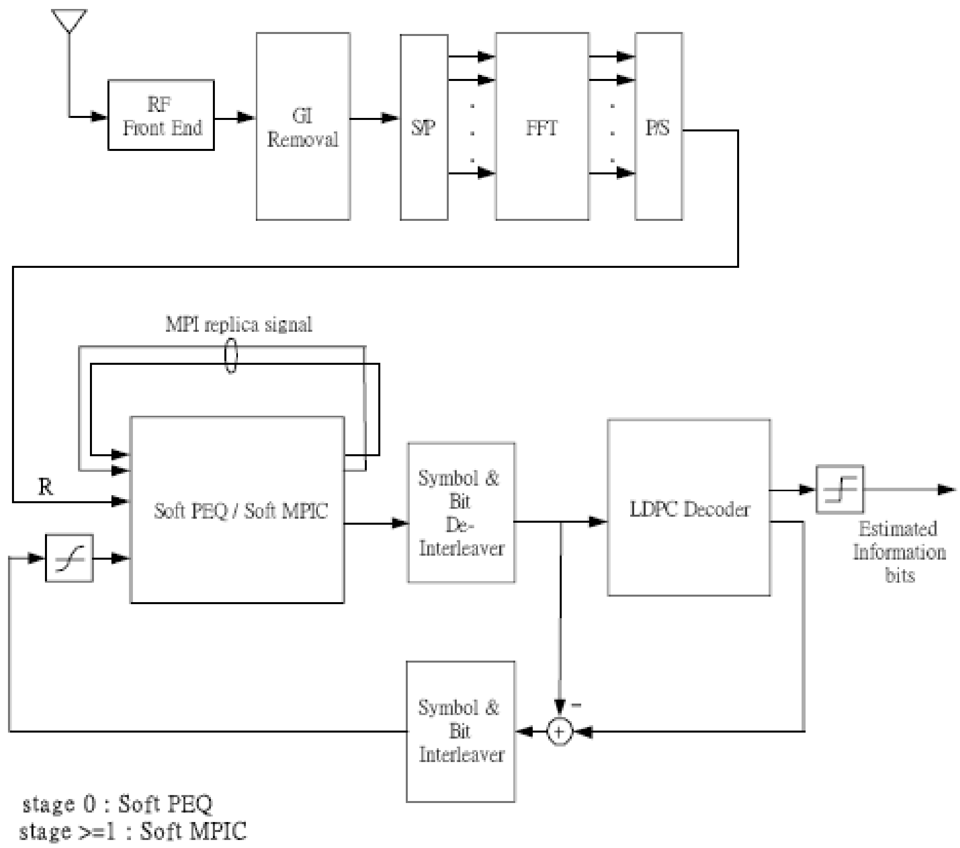

圖1-4 結合多重編碼改良系統下的渦輪等化技術架構圖

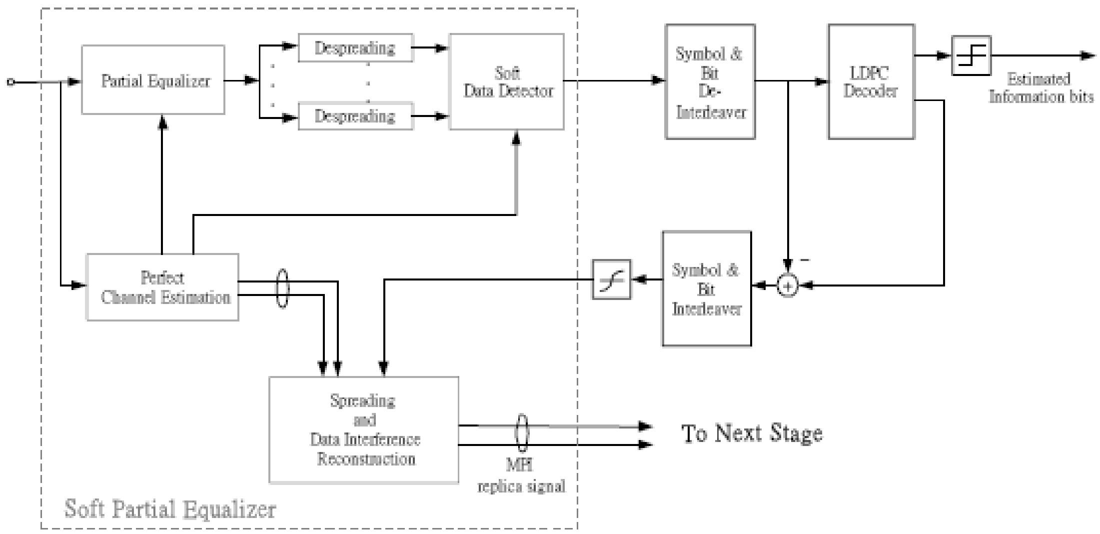

圖 1-5 渦輪等化技術第零級架構圖

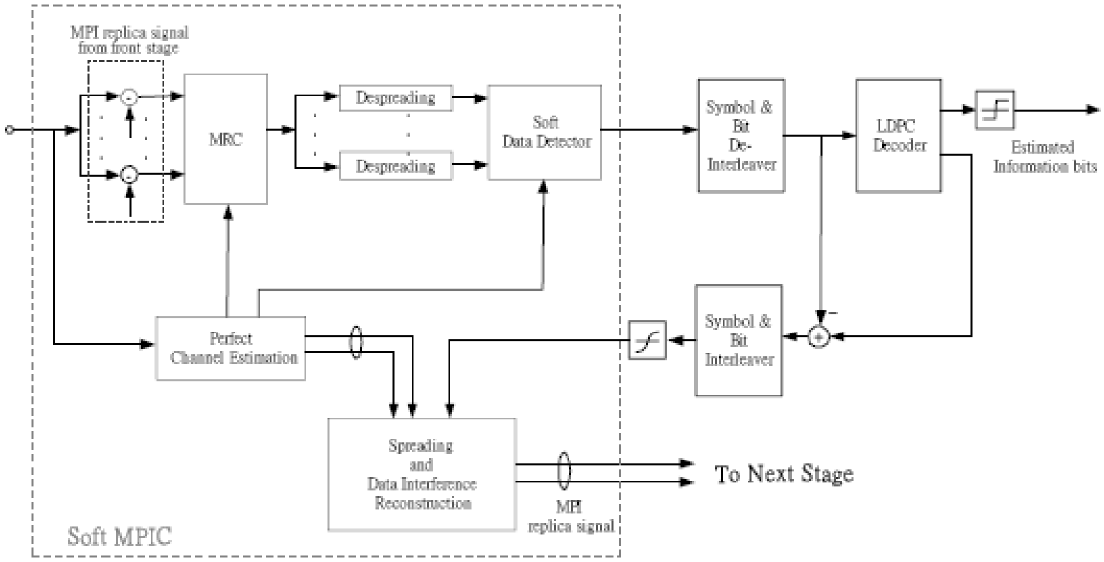

圖1-6 渦輪等化技術第一級(以上)架構圖

本計畫第三部份的主要研究目標，在設計一種適用於OFDMA系統之干擾協調方案，此方案著重於頻率與功率分佈(power profile)之干擾協調。研究方法可參閱圖1-7與圖1-8所示，我們優先考量靜態(static) 頻率與功率分佈之干擾協調架構，進而推展至可作動態(dynamic)模式選擇之方法。由於干擾協調已被視為是OFDMA系統解決細胞間干擾的主流技術，因此我們針對此一方向研究，提供未來Mobile WiMAX、3GPP LTE甚至是IEEE 802.16m的佈建上提供一有效的解決方案。其次是OFDM/CDMA架構之系統容量分析，我們參考歐規3GPP的CDMA時域展頻技術，由OFDM頻域展頻技術之處理增益來解決細胞間干擾問題，並進行以OFDM/CDMA架構為基礎之改良型Mobile WiMAX系統與傳統OFDMA為基礎之Mobile WiMAX系統容量(Capacity)比較。

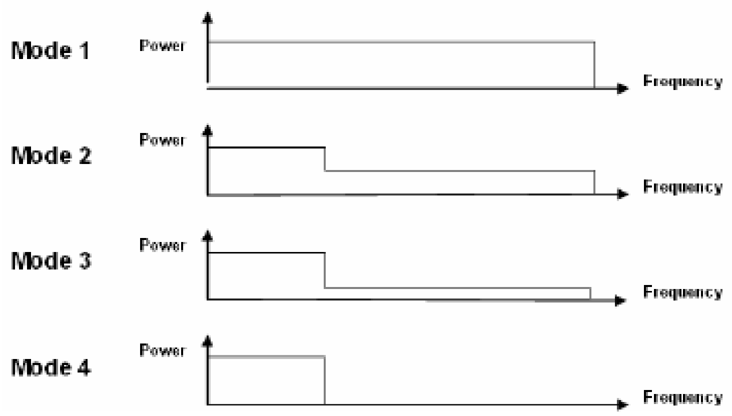

圖1-7 頻率與功率分佈之干擾協調架構一

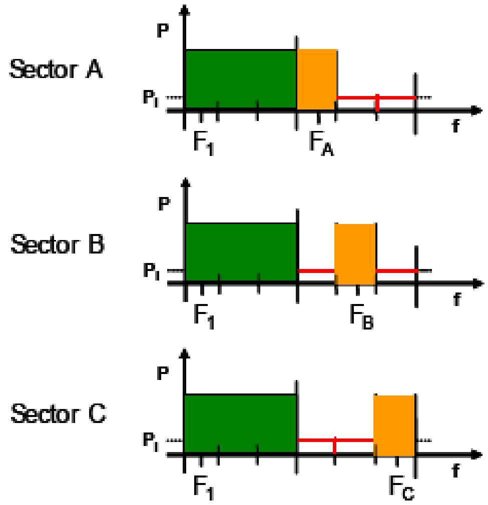

圖1-8 頻率與功率分佈之干擾協調架構二

第二章 Wimax-New 系統基本模型

本計畫針對行動 Wimax 系統，使用一種頻域展頻的技術，將訊號在頻域作正交展頻，使用此技術的目的在於將每個載波上的資訊能量分散到所有載波上，如此一來，可以改善 OFDMA 在嚴重通道衰變的情況下的訊號品質，因為從 OFDMA 的特性來看，訊號載波間的訊號是不相關，因此如果某幾個載波受到嚴重通道衰變干擾，訊號將可能會消失，因此要改善這個問題，必須使用資訊分散的方法，使用編碼技術是一種解決方案，本計畫採取頻域展頻的技術將可以更進一步提升系統效能。

較適合用於 OFDMA 系統的展頻碼是具有正交特性的華氏碼(Walsh code)，因為 Walsh code 具有正交特性，因此各載波展頻之後的訊號即使疊加起來也不會互相干擾，十分適合用於行動 Wimax 頻譜資源限制的特性，然行動 Wimax 之載波並無法符合 Walsh code 碼長需為 2 的多次方之限制，因此想出將訊號切割分組，以 FFT size 為 2048 點的例子，其實際使用的資料載波只有 1440 個，我們可將其切割分為四組，其對應長度分別為 1024，256，128，32，如此一來，每一分組將可符合 Walsh code 之規則，而且總長度又可符合行動 Wimax 的規定。每一分組可利用其組別內 Walsh code 作頻域展頻的動作，將訊號能量分散在所屬組別之所有載波上，接收端只要對對應之組別做相對應的解展頻作用，即可將各個載波的資訊還原，即使受到通道嚴重的衰變，解展頻之後的訊號還是會有相當品質的質量，可以讓資料偵測器正確解出資料。

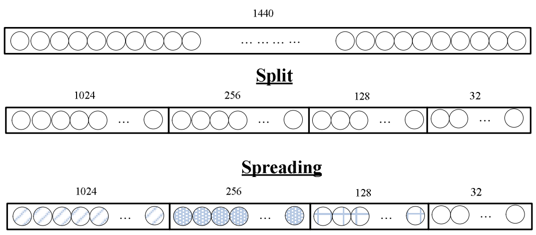

圖 2-1 行動 Wimax 載波分組及頻域展頻

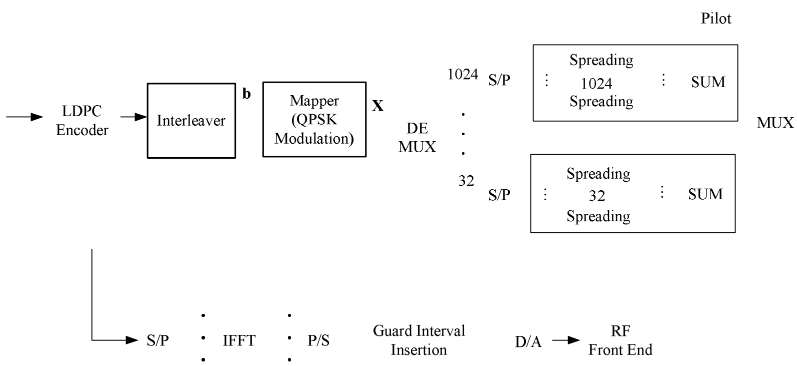

圖 2-2 具有多重碼特性之行動 Wimax 傳送端架構圖

圖 2-2 為行動 Wimax 傳送端的架構圖，在經過 LDPC code 編碼、交錯及調變之後，訊號將作分組動作，分組之後的訊號即進行對應組別的展頻，因為是在 IFFT 之前的展頻，因此其屬於頻域展頻。因為展頻碼具正交特性，各組的載波展頻之後將可以在各組內疊加起來，之後再將訊號多工串接起來，這時就可將領航載波(Pilot)加進 OFDM 符元內。經過 IFFT 之後，訊號即轉為時域訊號，加上護衛區間的保護，符元訊號即可從傳送端傳送出去。

本計畫另一核心技術在於接收端的多路徑干擾消除技術，此技術主要目的在於對抗通道多路徑干擾的效應，利用訊號偵測與重建之間的遞迴式訊號處理，以減小訊號受到通道衰變的效應，接收端的架構圖如圖 2-3 所示，訊號從通道接收之後，先轉到基頻，移除護衛區間之後，即可作數位訊號處理。FFT 將訊號由時域轉到頻域，因此接下來的訊號將會在頻域作運算，領航載波會用來作同步及相關系統參數之指定，而資料載波即可用來作多路徑干擾消除相關的訊號處理。這邊的多路徑干擾消除訊號處理即為圖中深色區塊的部份，詳細內容將在後面說明。訊號送進多路徑干擾消除訊號處理區塊之後，可以解出第一次的訊號估計，此估計出的訊號可以經過訊號重建的方式，將訊號重建為受通道干擾效應的狀態，再回授到多路徑干擾消除訊號處理區塊的輸入端，因為已經經過第一次的訊號估計，基本上已經消除部份的資訊不確定性，因此利用此估計過後的訊號再進行一次多路徑干擾消除訊號處理，將可以有更好的資料品質，經過多次遞迴之後，訊號將可以有越來越好的品質，經過模擬，約 3~4 次的遞迴運算即可有相當程度的改善。在多路徑干擾消除運算之後，訊號即可送到後端之低密度位元檢查碼作解碼之運算。

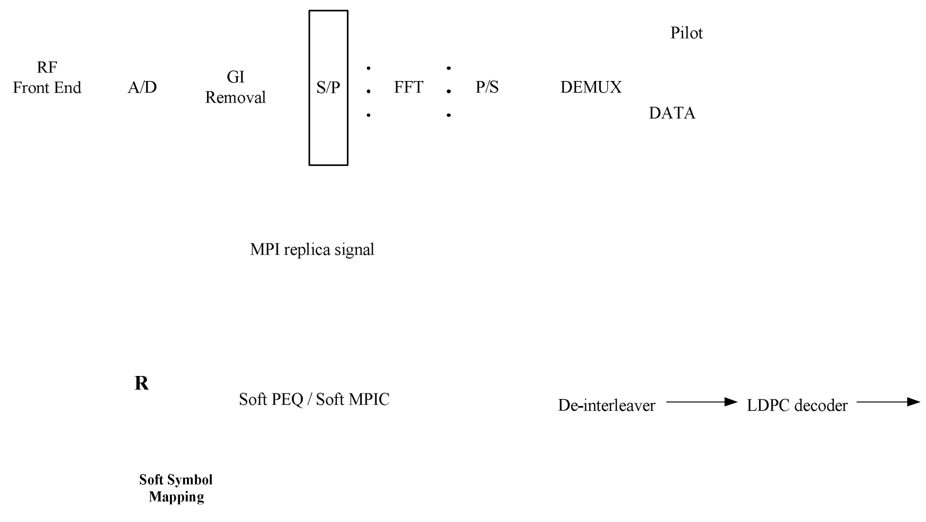

圖 2-3 具有多重碼及多路徑干擾消除技術之行動 Wimax 接收端架構圖

圖 2-4 為接收端軟式部份等化器的區塊架構圖，圖 2-5 為接收端軟式多路徑干擾消除運算之區塊架構圖。訊號會先經過第一次的軟式部份等化運算之後再作多路徑干擾消除運算，軟式部份等化運算之主要目的在於補償通道的效應，其等化參數

如式(2-1)所示，這邊之所以使用軟式等化器，在於可以依照通道的情形加以調整 β 值，如通道干擾是以 AWGN 為主，則將等化器調整趨近 MMSE 等化器的模式，如果通道干擾是以多載波之間的干擾為主，則可以調整 β 值趨近 ZF 等化器的模式，如果是介在中間則等化器亦可適應性校對到比較適合之型態，在這邊我們假設通道狀態資訊已知。

$$G_i = H_i^* / |H_i|^{1+\beta}, \qquad 0 \le \mathrm{i} \le (\mathrm{N}-1),\ -1 \le \beta \le 1 \tag{2-1}$$

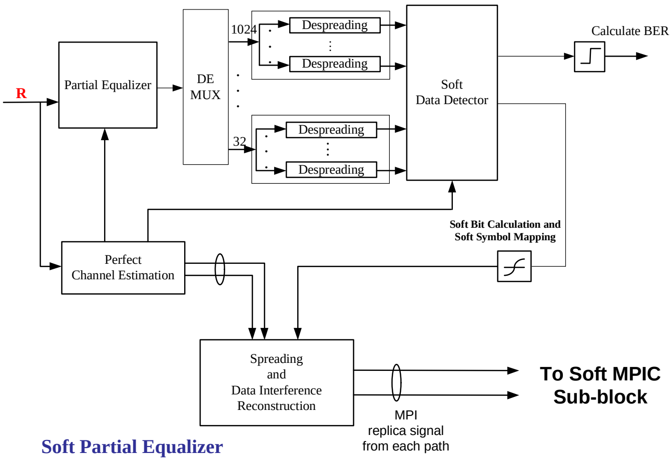

圖 2-4 行動 Wimax 接收端之軟式部份等化器區塊架構圖

經過等化之後的訊號即可做解展頻的動作，因為傳送端已有分組處理，因此接收端需要對相對應的訊號作分組運算，即對 1024，256，128，32 作對應之解展頻處理，解展頻之後的訊號可以表示為：

$$\begin{aligned} z_{l,k} &= \mathbf{c}_{l,k}^T \mathbf{G}_l \mathbf{r}_l \\ &= \mathbf{c}_{l,k}^T \mathbf{G}_l \left(\mathbf{H}_l \left(\sum_{j=1}^{l} x_j \mathbf{c}_{l,j} \right) + \mathbf{N} \right) \\ &= \sum_{i=1}^{l} \left(g_i h_i \sum_{j=1}^{l} x_j c_{l,k,i} c_{l,j,i} \right) + \mathbf{c}_{l,k}^T \mathbf{G}_l \mathbf{N} \\ &= \underbrace{x_k \sum_{i=1}^{l} g_i h_i}_{DS} + \underbrace{\sum_{\substack{j=1 \\ j \ne k}}^{l} \sum_{i=1}^{l} g_i h_i x_j c_{l,k,i} c_{l,j,i}}_{IS} + \underbrace{\sum_{i=1}^{l} c_{l,k,i} g_i n_i}_{NS} \end{aligned} \tag{2-2}$$

z 為解展頻之後的訊號，r 為接收的訊號，G 為軟式等化器，c 為展頻及解展頻用的華氏碼，l 為對應組別之長度，k 為組別內第 k 個載波，H 為通道效應，N 為通道雜訊，DS 為所要解出的訊號，IS 為碼際干擾，NS 為雜訊干擾。碼際干擾與雜訊干擾所提供的變異數將可用來計算軟性資訊。解展頻之後的訊號將可以作資料偵測，我們使用性能較好的軟式資料偵測，計算出其軟式資訊，因為訊號的實部與虛部互相獨立，因此其計算方式一樣，在這邊只推導實部的部份，虛部的部份可以用相同的步驟計算。

軟式資訊：

$$\Gamma_{k,\mathrm{Re}} = \ln \frac{P\left(\mathrm{Re}\{x_k\} = +1/\sqrt{2} \mid \mathrm{Re}\{z_{l,k}\}\right)}{P\left(\mathrm{Re}\{x_k\} = -1/\sqrt{2} \mid \mathrm{Re}\{z_{l,k}\}\right)} = \ln \frac{P\left(\mathrm{Re}\{z_{l,k}\} \mid \mathrm{Re}\{x_k\} = +1/\sqrt{2}\right)}{P\left(\mathrm{Re}\{z_{l,k}\} \mid \mathrm{Re}\{x_k\} = -1/\sqrt{2}\right)} \quad (2\text{-}3)$$

$$P\left(\mathrm{Re}\{z_{l,k}\} \mid \mathrm{Re}\{x_k\} = +\frac{1}{\sqrt{2}}\right) = \frac{1}{\sqrt{2\pi\sigma^2_{\mathrm{Re}\{z\}}}} \exp\left(-\frac{\left(\mathrm{Re}\{z_{l,k}\} - m_{\mathrm{Re}\{z\}}\right)^2}{2\sigma^2_{\mathrm{Re}\{z\}}}\right) \quad (2\text{-}4)$$

$$P\left(\mathrm{Re}\{z_{l,k}\} \mid \mathrm{Re}\{x_k\} = -\frac{1}{\sqrt{2}}\right) = \frac{1}{\sqrt{2\pi\sigma^2_{\mathrm{Re}\{z\}}}} \exp\left(-\frac{\left(\mathrm{Re}\{z_{l,k}\} + m_{\mathrm{Re}\{z\}}\right)^2}{2\sigma^2_{\mathrm{Re}\{z\}}}\right) \quad (2\text{-}5)$$

$$\Gamma_{k,\mathrm{Re}} = \frac{1}{2\sigma^2_{\mathrm{Re}\{z\}}} \left\{\left(\mathrm{Re}\{z_{l,k}\} + m_{\mathrm{Re}\{z\}}\right)^2 - \left(\mathrm{Re}\{z_{l,k}\} - m_{\mathrm{Re}\{z\}}\right)^2\right\} \quad (2\text{-}6)$$

計算出軟式資訊之後，透過轉換可將軟式資訊轉換為軟位元，

$$\mathrm{Re}\{\hat{x}_k\} = 1/\sqrt{2}\tanh(\Gamma_{k,\mathrm{Re}}/2) \quad (2\text{-}7)$$

$$\mathrm{Im}\{\hat{x}_k\} = 1/\sqrt{2}\tanh(\Gamma_{k,\mathrm{Im}}/2) \quad (2\text{-}8)$$

$$\hat{x}_k = \mathrm{Re}\{\hat{x}_k\} + j\,\mathrm{Im}\{\hat{x}_k\} \quad (2\text{-}9)$$

軟位元即可用來做訊號重建，訊號重建包括重新展頻與加入通道資訊，因此可以重建出多路徑訊號，由於這邊經過第一次資料偵測的動作，因此重建的訊號將有更好的訊號品質，用這訊號做再一次的訊號處理，即遞迴運算(下一級為多路徑干擾消除運算)，即可獲得更好的性能表現，重建之後的訊號即送到下一級的多路徑干擾消除運算，多路徑干擾消除運算區塊架構圖如圖 2-5 所示：

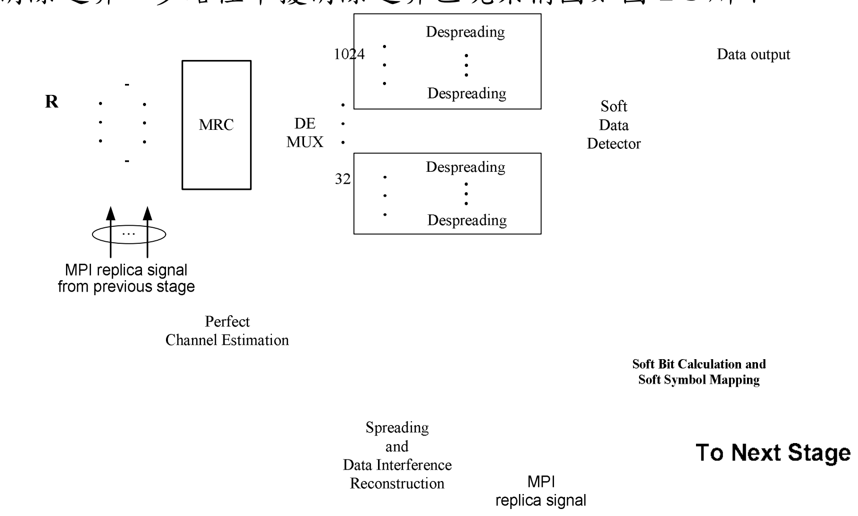

圖 2-5 行動 Wimax 接收端之軟式多路徑干擾消除區塊架構圖

由於在本級之前，多路徑訊號已被分解出來，因此在本級即可利用最大比合併(MRC)的方式將訊號的能量集合起來。第一步驟即為多路徑干擾消除(假設共有 n 個路徑訊號)，接收的訊號 R 扣除其他 n-1 條前一級所重建出的訊號，即可將第一條路徑訊號分解出來，其它 n-1 條路徑亦可使用一樣的方式解出來，解出的路徑如

式(2-10)所示：

$$\mathbf{r}_d = \mathbf{R} - \left(\sum_{\substack{i=1 \\ i \neq d}}^{P} \mathbf{H}_i \right) \left(\sum_{k=1}^{l} \hat{x}_k \mathbf{c}_k \right), \qquad 1 \leq \mathrm{d} \leq \mathrm{P} \tag{2-10}$$

因此在這一級解出的 n 條路徑即可用最大比合併將訊號能量集合起來，也因為有這一步驟，提升了系統的效能，之後再經過對應之解展頻動作與軟式資訊偵測，即可將訊號的軟式資訊解出來，如式(2-11)所示：

$$\Gamma_k = (2 / N_s \sigma_n^2) \cdot \mathbf{c}_k^T \sum_{d=1}^{P} \mathbf{H}_d^* \mathbf{r}_d \tag{2-11}$$

軟式資訊經過轉換可以轉換為軟位元，如式(2-12)所示：

$$\hat{x}_k = 1/\sqrt{2} \tanh\left(\mathrm{Re}\{\Gamma_k\}/2\right) + j(1/\sqrt{2}) \tanh\left(\mathrm{Im}\{\Gamma_k\}/2\right) \tag{2-12}$$

軟位元即可用來作訊號重建，重建的訊號會包括重新展頻與加入通道的效應，之後將重建好的訊號送到下一級的多路徑干擾消除運算，由於之後的訊號都有經過訊號重建，因此之後每一次的遞迴運算只需作多路徑干擾消除運算即可，不用再作軟式等化處理。經過幾次的多路徑干擾消除運算，最後的位元資訊即可送到後端的解碼器作解碼工作，這邊的解碼我們使用的是低密度位元檢查碼(LDPC)。

行動 Wimax 對於 LDPC code 有相當的定義，對於不同碼率與碼長均運用對應的基本矩陣(base matrix)

$$H = \begin{bmatrix} P_{0,0} & P_{0,1} & P_{0,2} & \cdots & P_{0,n_b-2} & P_{0,n_b-1} \\ P_{1,0} & P_{1,1} & P_{1,2} & \cdots & P_{1,n_b-2} & P_{1,n_b-1} \\ P_{2,0} & P_{2,1} & P_{2,2} & \cdots & P_{2,n_b-2} & P_{2,n_b-1} \\ \vdots & \cdots & \cdots & \cdots & \cdots & \vdots \\ P_{m_b-1,0} & P_{m_b-1,1} & P_{m_b-1,2} & \cdots & P_{m_b-1,n_b-2} & P_{m_b-1,n_b-1} \end{bmatrix} \tag{2-13}$$

其中 P 為 z*z 的交換矩陣(單位矩陣的位移矩陣)或是零矩陣，某一碼率之基本矩陣為固定式，依照碼長不同而適時調整 z 的大小，以符合所需要的對應位元檢查碼矩陣，以碼率為 1/2 為例子，其基本矩陣為：

-1	94	73	-1	-1	-1	-1	-1	55	83	-1	-1	7	0	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
-1	27	-1	-1	-1	22	79	9	-1	-1	-1	12	-1	0	0	-1	-1	-1	-1	-1	-1	-1	-1	-1
-1	-1	-1	24	22	81	-1	33	-1	-1	-1	0	-1	-1	0	0	-1	-1	-1	-1	-1	-1	-1	-1
61	-1	47	-1	-1	-1	-1	-1	65	25	-1	-1	-1	-1	-1	0	0	-1	-1	-1	-1	-1	-1	-1
-1	-1	39	-1	-1	-1	84	-1	-1	41	72	-1	-1	-1	-1	-1	0	0	-1	-1	-1	-1	-1	-1
-1	-1	-1	-1	46	40	-1	82	-1	-1	-1	79	0	-1	-1	-1	-1	0	0	-1	-1	-1	-1	-1
-1	-1	95	53	-1	-1	-1	-1	-1	14	18	-1	-1	-1	-1	-1	-1	-1	0	0	-1	-1	-1	-1
-1	11	73	-1	-1	-1	2	-1	-1	47	-1	-1	-1	-1	-1	-1	-1	-1	-1	0	0	-1	-1	-1
12	-1	-1	-1	83	24	-1	43	-1	-1	-1	51	-1	-1	-1	-1	-1	-1	-1	-1	0	0	-1	-1
-1	-1	-1	-1	-1	94	-1	59	-1	-1	70	72	-1	-1	-1	-1	-1	-1	-1	-1	-1	0	0	-1
-1	-1	7	65	-1	-1	-1	-1	39	49	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	0	0
43	-1	-1	-1	-1	66	-1	41	-1	-1	-1	26	7	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	0

每一個 element 都是一個 z*z 矩陣，數字部份則為此 z*z 單位矩陣向右循環平移的

量，基本矩陣的 column 為 24*z=n，因此給定一個碼長，即可計算出 z 的大小，再將 z*z 矩陣向右循環平移，即可產生所使用之位元檢查碼矩陣(parity check matrix)，編碼器與解碼器都使用相同的位元檢查碼矩陣來做編碼與解碼的動作。

第三章 Wimax-New 系統進階設計

本計畫延伸Wimax-New基本系統模型,將渦輪遞迴式運算的概念加進系統裡。我們的研究重點條列於下：

第一點，本計畫使用具有正交特性之華氏展頻碼，將一個頻域載波的訊號，利用展頻的原理，將其均勻放置在所有的頻域載波上面，每個頻域載波的訊號都做一樣的動作，再將這全部載波的訊號疊加一起，如此一來，原本每一個載波的訊號會均勻由所有的載波傳送，頻域展頻後的每一個載波將會載有原本全部載波的訊號，由於使用華氏碼，每個載波上的所有原有載波訊號將會因為具有正交特性，而不會互相干擾，只要在接收端部份做對應的解展頻動作，將可以把所有的載波資料還原回來，而且因為使用展頻碼的關係，系統可以具有展頻增益而提升效能。

第二點，本計畫使用軟式等化器在頻域將通道效應補償，因為由標準所訂定的領航載波雖然較資料載波有2.5dB的增益，但是如果多路徑衰變通道如果很劇烈，原本少數數量的領航載波將不足以提供接收機作準確的通道估計，而在不準的通道資訊，如果使用傳統的單一支路等化器，將會把整體訊號嚴重錯估，因此本計畫使用軟式等化器，可以減緩通道估計不準對資料偵測的影響。

第三點，本計畫使用軟式資料偵測器。本計畫使用以機率為基底之最大相似比軟式資料偵測器，由於針對訊號經過通道的機率模型，對訊號做可靠度分析運算，因此可以計算每一個資料位元的可靠度，每一個位元的可靠度可以透過轉換，轉換為軟位元,以提供資料分析之用.每一個位元之可靠量度值可以提供給低密度同位檢查碼之通道解碼器做解碼運算.

第四點，本計畫使用多路徑干擾消除技術。因為在都市無線通道的環境，主要是以多路徑通道為主，因此接收機會接收到多路徑的訊號，而這多路徑訊號將會破壞華氏碼的正交特性，因此有必要將多路徑訊號區分.而且因為每個路徑皆載有訊號，如可以將多路徑訊號分解，將可以利用最大比合併的方式，將每個路徑之能量集合起來，如此一來，將可以提升訊號對抗雜訊的能力，而且可以讓展頻碼的展頻增益發揮到最佳程度。

第五點，本計畫使用智慧型渦輪等化技術。因為即使使用通道編碼技術，系統效能仍會受限於多路徑干擾影響，因此本計畫將渦輪等化技術與通道低密度同位檢查解碼器結合，利用解碼器所計算之後置機率，重建出每個路徑的軟式符元訊號，而每個路徑的軟式符元訊號將可以回授給多路徑干擾消除模組，進行多路徑干擾消除運算，如此一來，經過幾個遞迴運算，系統將可以具有很好的性能。

Wimax-New 系統模型

本計畫所設計之新型Wimax系統具有多重碼之特性，其傳送端架構與資料結構如圖3.1所示，本計畫所採用的領航載波模式是以Wimax標準之FUSC模式為主。

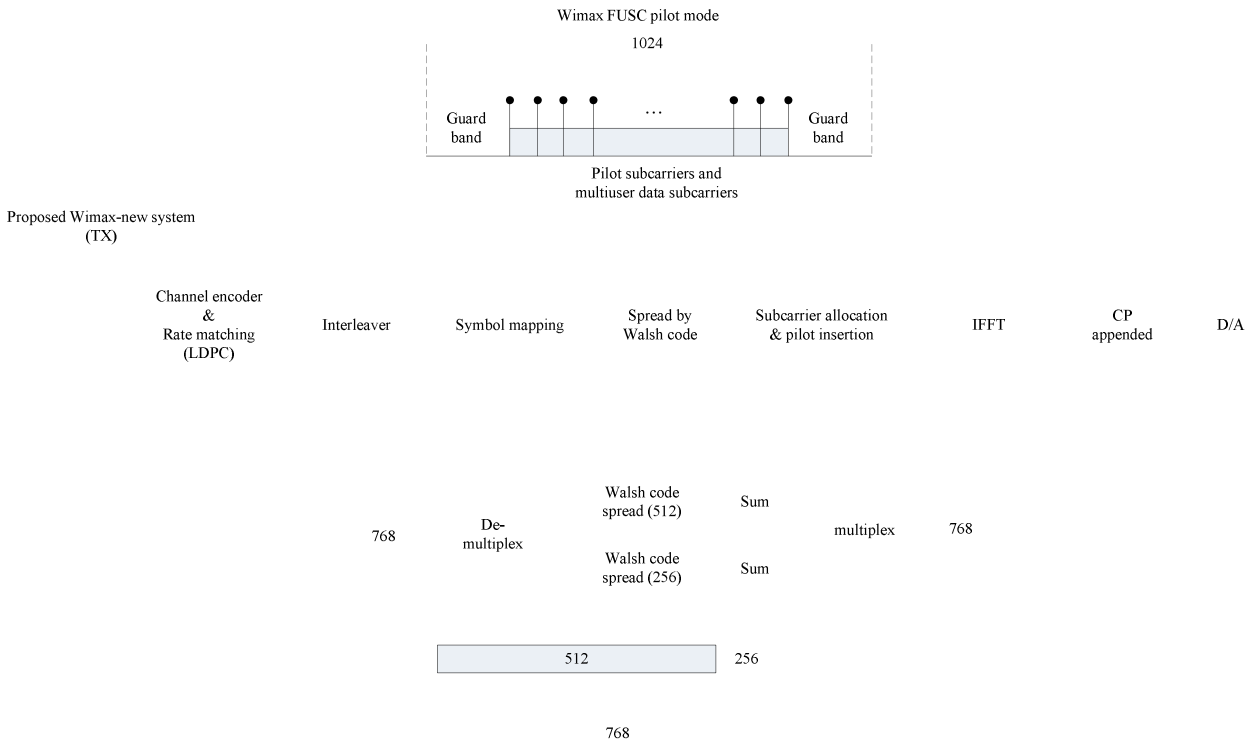

圖3-1 Wimax-New傳送端模型與訊號載波設計

Wimax之資料流初步經由低密度同位檢查編碼器編碼處理，碼率可由系統依照通道品質做適時調整，所使用之編碼方式會在後面章節說明.編碼之後的訊號會經過交錯器處理，交錯器會將訊號的位置調換，相臨的位元訊息將會互相遠離，使用交錯器的目的是要減低叢集錯誤對更正碼的影響，以提高更正碼保護的能力.接著訊號將會依照使用符元的方式，將位元訊號組合為符元訊號.符元訊號會進行頻域的展頻處理，本計畫所採用的是Wimax規格內之FUSC模式，因此真正載資料的載波數目只佔整體的一部份，以1024點模式為例，資料載波有768個，領航載波有96個，其餘為護衛區間，領航載波限定用BPSK調變，不適合進入展頻，因此真正有需要展頻為資料載波，在Wimax系統裡，因為使用OFDMA方式，因此這邊的資料載波包含很多不同使用者之資料載波，每個使用者依照系統分配，使用特定的子通道載波。本計畫使用具有正交特性的華式碼展頻，華氏碼的規則是展頻長度必須為2的N次方，因此我們在這邊可以將資料載波區分成長度為512及256的資料區塊，如此一來本來無法使用展頻碼的資料載波將可以使用展頻碼展頻.展頻之後的資料載波，將加入領航載波與護衛區間，領航載波之功率強度較一般資料載波高2.5dB，主要是用來作接收機之通道估計之用，護衛區間則是用來保護資料區塊，以避免不同OFDM符元之間互相干擾.接著整個載波區塊將做IFFT運算，即OFDM調變，以最新的行動式Wimax標準(2009)，FFT長度設定為512點及1024點二種.經過IFFT運算，訊號即由頻域轉到時域，接著加入護衛區間，護衛區間的目的，是要保護整個OFDM符元可以對抗多路徑通道之影響，一般標準設定值為符元長度之1/8.多路徑之最大延遲如果在護衛區間裡面，符元均可透過通道估計將通道效應還原.經過D/A轉換後，訊號即

由傳送端發送出去。
接收端方面，如圖3-2所示：

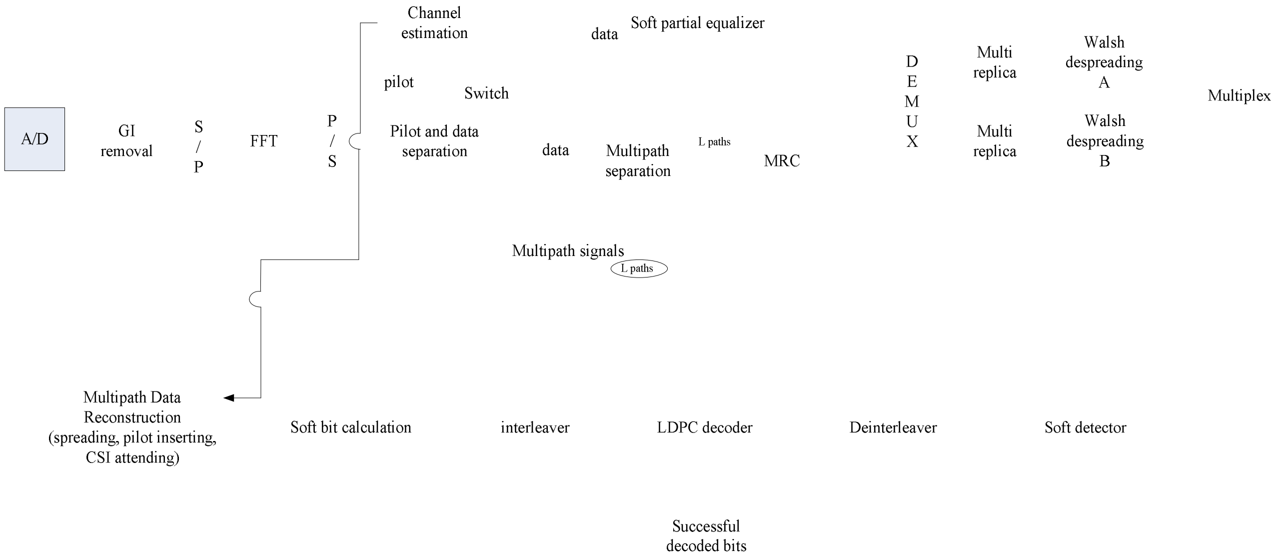

圖3-2 Wimax-New接收端模型

接收到的訊號會先進行A/D轉換為數位訊號，接著移除護衛區間，移除護衛區間的OFDM符元即可進行FFT運算，即OFDM之解調，訊號將會從時域轉至頻域，在本系統設計裡，我們假設系統已同步；OFDM之次載波包含領航次載波與資料次載波，因此在完成FFT運算之後，領航次載波會提出到通道估計模組，進行通道估計工作，本系統採用FUSC模式，因此我們可以利用領航次載波之特性進行通道估計，估計出的通道資訊會送到軟式部份等化器.本系統採用的是遞迴式多層次運算，因此不同遞迴所經過的訊號處理會不一樣，第一次的運算是軟式部份等化訊號處理，第二次以後的運算是軟式連續式多路徑干擾消除訊號處理，訊號處理由切換器依照遞迴次數做選擇動作。

第一次運算是使用軟式部份等化器，主要功能是抵消接收訊號受到通道的影響，等化器所使用的通道參數由通道估計模組所估計的通道資訊計算出來，主要是因為通道估計不一定準確，如果直接使用反轉等化，將會造成雜訊放大的現象，因此我們使用軟式部份等化的方式，由一beta參數來調整等化器的等化參數，如此一來會有較佳的等化效果。等化之後的接收訊號即已補償通道的效應，因此可以進行解展頻，本系統的解展頻運算是在頻域來運作.因為使用華氏碼，接收機所使用的華氏碼需要對應傳送端所使用的華氏碼，有二種不同的長度會對應其相關的華氏碼，解展頻之後的訊號就可以進行資料偵測的工作.本系統採用軟式資料偵測的方法，利用機率模型與最大相似比方法，算出每個位元之對數相似比值，由於是使用機率的方式計算每個位元的資訊，因此資料偵測的效果會比一般硬式資料偵測的方法還要好.計算出之位元資訊，經過解交錯器之解交錯的動作之後，即可送到後面解碼器作解碼的運算.本系統使用高效能之低密度同位檢查碼解碼器來解碼，由於傳統的低密度同位檢查碼解碼方式運算複雜度太高，因此在這邊我們使用最大對數的解碼方

法，在輕微減低系統效能的情況下，可以大幅減低運算複雜度，因此可以加快解碼器的運算效果.低密度同位檢查碼解碼器會在解碼器內部作多次的解碼遞迴運算，每次遞迴運算都可以增加解碼的效果。最後解碼器會計算出一組後置機率，根據這組後置機率，我們可以判斷系統是否已完全更正傳輸訊號受到通道影響而產生的位元錯誤，如果解碼器已成功解碼，則訊號即可送到外部之處理器進行其它訊號處理.如果訊號經過解碼器判斷並未全部正確，則接收機會開啟之後的軟式連續式多路徑干擾消除訊號處理。軟式連續式多路徑干擾消除訊號處理主要功能，在於利用前一次運算所建立的多路徑訊號，將真正接收訊號的多路徑訊號區分開來，因此在前一次運算，我們可以根據解碼器所計算的後置機率重建訊號.解碼器所算出的後置機率值經過交錯器之後，進入軟位元計算轉換模組，這裡會將後置機率值轉換為軟位元並將之組合調變為軟符元，接著軟符元會進行華氏碼分組與展頻，之後會加入領航符元，重建的訊號會根據真實通道狀態資訊(CSI)重建出每個路徑的訊號，如此L條路徑的訊號都可以被重建出來，接著這些重建的路徑訊號會送到下一個遞迴的軟式連續式多路徑干擾消除訊號處理模組。

由於新的遞迴是軟式連續式多路徑干擾消除訊號處理，因此切換器會切換到這個路線，首先要把每個接收訊號的路徑區分開來，因此第i條路徑的訊號為接收訊號扣除路徑i以外的其它重建路徑訊號，如此一來，重建的第i條訊號只包括第i條路徑的訊號，雜訊，及其它殘餘估不準路徑的訊號，每一條路徑都可以透過這個方法將其它多路徑干擾的訊號消除.訊號處理之後，每個路徑都將是單一路徑，有其本身對應的通道效應,因此重建出的L條單一路徑只會有其對應的L個單一通道效應.經過多路徑干擾消除的運算，可以利用最大比合併的方式將所有的路徑訊號依照通道強度予以加強及合併，因此可以有非常好的訊號品質.經過最大比合併的訊號接下來繼續做解展頻，解交錯及低密度同位檢查碼解碼的運算.經過解碼之後，可以再判斷新的遞迴所計算出的後置機率是否已經將接收訊號正確解出，如果正確解出，則可以將訊號送到其它處理器運算，如果檢查仍有錯誤，就繼續軟式連續式多路徑干擾消除訊號處理的遞迴。

經過每次遞迴，多路徑的訊號可以越來越清楚，因此經過最大比合併的訊號也會有越好的訊號品質，再加上低密度同位檢查碼解碼的運算，系統整體的效能將可以提升。

<u>*接收機數學演算法*</u>

接收機第一個遞迴運算是軟式部份等化器，其等化係數如式子所示

$$G_i = H_i^* / \left|H_i\right|^{1+\beta}, \qquad 0 \le \mathrm{i} \le (\mathrm{N}-1),\ -1 \le \beta \le 1 \qquad (3\text{-}1)$$

其中H代表估計的通道，G代表等化器之等化係數，β為等化器之調整參數，我們可以依照通道的品質設定不同的調整參數，當調整參數設定為1時，此一等化器近似為零級強力反轉等化器，當調整參數設定為0時，此一等化器近似為相等增益等化器，當調整參數設定為-1時，此一等化器近似為最大比合併等化器，當調整參數設定為其它值，其具有綜合特性，因此可以利用此一軟式部份等化器來提高等化品質。

經過解展頻之後，訊號會進行軟式資料偵測運算，軟式資料偵測運算是利用中央極限定理，找出資料的機率模型，在依照機率模型計算出其對數相似比值。所使用的機率模型如式子所示：

$$P\left(z_{l,k} \mid x_k = s_i\right) = \frac{1}{\sqrt{2\pi\sigma_z^2}} \exp\left(-\frac{\left(z_{l,k} - m_z\right)^2}{2\sigma_z^2}\right) \tag{3-2}$$

其中平均值與變異數的運算為

$$m_z = x_k \sum_{i=1}^{l} g_i h_i \tag{3-3}$$

$$\sigma_z^2 = (l-1)\sum_{i=1}^{l} {\psi_i}^2 + \sigma_n^2 \sum_{i=1}^{l} \left|g_i\right|^2 \tag{3-4}$$

$$\psi_i = g_i h_i - \frac{1}{l}\left(\sum_{j=1}^{l} g_j h_j\right) \tag{3-5}$$

因此我們可以用此方式算出每個位元的對數相似比值。

$$\Gamma_{z,b_i} = \ln \frac{\sum_{z_i \in \{b_i = 1\}} P_{z_i}}{\sum_{z_i \in \{b_i = -1\}} P_{z_i}} \tag{3-6}$$

接著就可以把每個位元的對數相似比值送到低密度同位檢查碼解碼器作解碼運算.解碼正確的位元即送到其它處理器作運算，如果解碼之後仍有部份錯誤，就需要進行下一遞迴之運算.開始下一遞迴之運算需要先將多路徑訊號重建，重建所使用的資料就是本次遞迴所估算出來的資訊.首先，將低密度同位檢查碼解碼器送出來的對數相似比值轉換為軟位元及軟符元。

$$\hat{x}_k = 1/\sqrt{2}\left[\tanh(\Gamma_{2k-1}/2) + \tanh(\Gamma_{2k}/2)\right] \tag{3-7}$$

軟符元會在加入領航符元及通道狀態資訊之後，送到下一遞迴之多路徑干擾消除運算，如式子所示

$$\mathbf{r}_d = \mathbf{R} - \left(\sum_{\substack{i=1 \\ i \neq d}}^{P} \mathbf{H}_i\right)\left(\sum_{k=1}^{l} \hat{x}_k \mathbf{c}_k\right), \qquad 1 \le \mathrm{d} \le \mathrm{P} \tag{3-8}$$

接著就是進行解展頻與軟式資料偵測的運算，在這一級因為多路徑干擾的影響已消除，因此資料偵測所用的模式可以簡化，其變異數可以不需要考慮展頻在多路徑的影響.經過資料偵測之後,就是進行低密度同位檢查碼解碼運算.經過多次渦輪運算， 可以提升系統的效能。

<u>低密度同位檢查碼</u>

本系統使用的低密度同位檢查碼依照Wimax標準作設計.在編碼端我們使用里察德森法作編碼，此係利用同位檢查矩陣的特性作編碼，如此一來可以較傳統低密度同位檢查碼編碼減低運算複雜度.解碼方面本系統使用最大對數法作解碼，如此可

以較傳統低密度同位檢查碼解碼的方式減低運算複雜度，以下為本系統低密度同位檢查碼解碼的演算法：

1. 初始化

   將軟式資料偵測器所計算之對數相似比值送至每一個對應之位元節點,每一位元節點再將其所接收的內質機率(對數相似比值)傳送到與其連接之所有檢查節點。

2. 計算所有位元節點端送到檢查節點端的機率訊息：

$$LLR^{(K)}(q_{ji}) = LLR(p_i) + \sum_{j' \in M(i) \backslash \{j\}} LLR^{(K-1)}(r_{j'i}) \qquad (3\text{-}9)$$

   其中 K 代表遞迴的次數，M(i)\{j}代表除了目標物檢查節點 (j) 以外，其他檢查節點送訊息到這個位元節點 (i) 的檢查節點集合。

3. 計算所有檢查節點端送到位元節點端的機率訊息：

$$LLR(r_{ji}) = (-1)^{|L(j)|}\left(\prod_{i' \in L(j)\backslash\{i\}} \operatorname{sgn}\left(LLR^{(K)}(q_{ji'})\right)\right) \cdot \Psi\left(\sum_{i' \in L(j)\backslash\{i\}} \Psi\left(\left|LLR^{(k)}(q_{ji'})\right|\right)\right) \qquad (3\text{-}10)$$

   利用 $\Psi(x) = -\log\left(\tanh(\frac{x}{2})\right) = \log\left(\frac{1+\exp(-x)}{1-\exp(-x)}\right)$ 函數的特性，可以將式子簡化為下列式子，使用簡化後的式子可以大大減低運算複雜度。

$$LLR(r_{ji}) = (-1)^{|L(j)|}\left(\prod_{i' \in L(j)\backslash\{i\}} \operatorname{sgn}\left(LLR^{(K)}(q_{ji'})\right)\right) \cdot \min_{i' \in L(j)\backslash\{i\}}\left(\left|LLR^{(k)}(q_{ji'})\right|\right) \qquad (3\text{-}11)$$

4. 計算後置機率

   利用初始狀態外部送進低密度同位檢查碼解碼器的本質機率(intrinsic probability) LLR(pi)，及經過低密度同位檢查碼解碼器運算所解出的外在機率(extrinsic probability)，即可計算出後置機率(posterior probability) $LLR^{(k)}(q_i)$:

$$LLR^{(k)}(q_i) = LLR(p_i) + \sum_{j \in M(i)} LLR^{(k-1)}(r_{ji}) \qquad (3\text{-}12)$$

   計算出後置機率之後，即可利用硬式判斷(hard decision)解出資訊位元是”0”還是”1”：

$$\hat{v}_i^{(k)} = \begin{cases} 1, & \text{if } LLR^{(k)}(q_i) \ge 0 \\ 0, & \text{if } LLR^{(k)}(q_i) < 0 \end{cases} \qquad (3\text{-}13)$$

   $\hat{v}_i^{(k)}$ 即代表解碼後的碼字(codeword)。

5. 計算徵兆

由以上步驟可以計算出碼字，再利用區塊碼的特性，碼字與同位檢查矩陣相乘，所計算出之徵兆應該為 0，$\mathbf{H}\hat{\mathbf{V}}^{\mathbf{T}} = \mathbf{0}$，測試所解碼出來的碼字是否為正確的碼字，如果符合徵兆為 0 的條件，此碼字即為正確的解碼碼字，亦即傳送端送出來的碼字，如果不符合徵兆為 0 的條件，則重覆上述第 2 到第 5 的步驟，一直到符合徵兆條件，或遞迴數達到最大的預設值為止。

第四章　系統模擬結果

表4.1 模擬參數

模擬系統	Wimax-New
使用頻段	2.5GHz
訊號頻寬	11.2MHz
FFT長度（符元長度）	1024
資料載波數	768
領航載波	96
左護衛載波	80
右護衛載波	79
DC 載波	1
載波間隔	10.94kHz
符元時間（不含護衛區間）	91.4usec
護衛區間 (1/8)	11.4usec
模擬用戶數	4
資料載波調變	QPSK
領航載波調變	BPSK （需高於資料載波2.5dB）
通道編碼	LDPC
碼率	1/2
編碼長度	1536
編碼參數 Zm	64
LDPC內部最大遞迴次數	10
系統整體遞迴最大次數	6
華氏碼展頻	512+256
軟式等化器參數beta	0.5
模擬車速	30km/hr， 90km/hr
最大都卜勒頻率	69.44 Hz， 208.33Hz
模擬通道	ITU-PED B 通道模型
通道衰變模型	雷利衰變模型
通道數目	6
通道增益規模(dB)	[0，-0.9，-4.9，-8.0，-7.8，-23.9]
通道延遲規模(samples)	[0， 2， 9， 14， 26， 42]

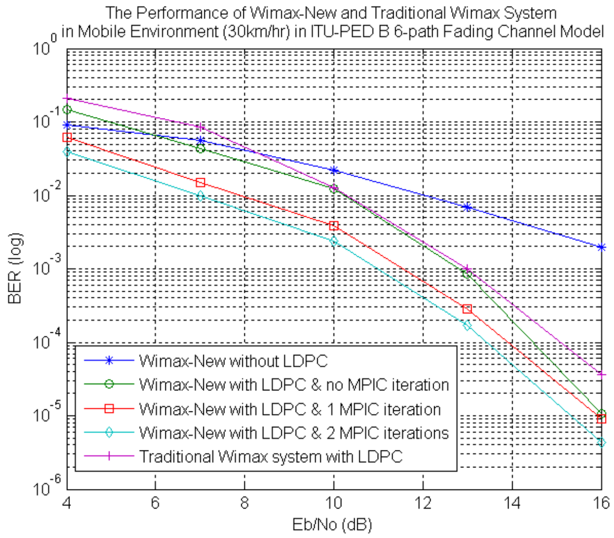

圖4-1 Wimax-New與傳統Wimax系統之比較
(車速30km/hr，編碼碼率1/2，模擬通道ITU PED-B 通道)

圖4-1為本系統設計Wimax-New系統與傳統Wimax系統之效能比較，為了比較公平，二個系統都使用相同的LDPC碼，接收機方面，二個系統都使用軟式部份等化器與軟式資料偵測器，二個系統的差異，在於Wimax-New系統使用多重碼展頻，與多層次軟式連續式多路徑干擾消除技術，而傳統的Wimax系統不使用.由電腦模擬，在ITU PED-B 6路徑瑞雷衰變通道底下，以車速30km/hr的表現來看，在10的-3次方等級的表現，本系統設計如果沒有遞迴，系統效能跟傳統系統差不多，但如果使用第一次軟式多路徑干擾消除，則系統效能可以提升1.5dB，如果使用二次軟式多路徑干擾消除，則系統效能可以提升2dB.由模擬可以得知，本系統設計使用LDPC碼與沒有使用LDPC碼的差異，如果沒有遞迴運算，編碼增益約為4dB，如果有多次遞迴運算，整體效果可以提升6dB左右。

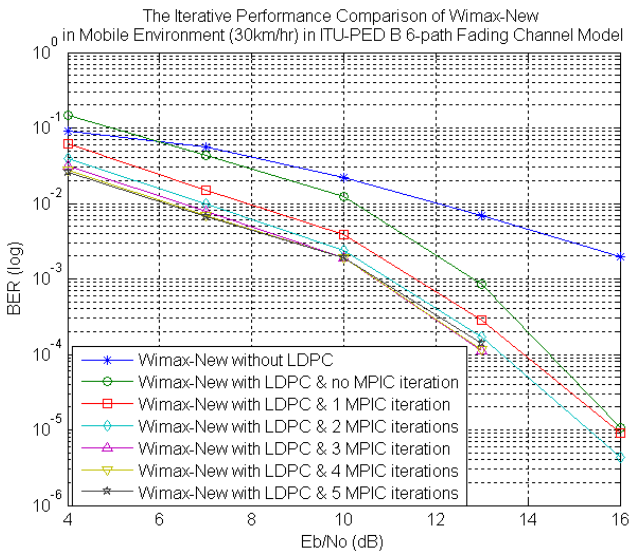

圖4-2 Wimax-New系統於不同遞迴訊號處理之性能比較
(車速30km/hr，編碼碼率1/2，模擬通道ITU PED-B 通道)

圖4-2為本系統設計於車速30km/hr的6路徑瑞雷衰變通道，在不同遞迴運算的效能比較，由模擬可以知道，在遞迴次數越多的運算，系統效能可以越提升，不過提升的速率也會慢慢收斂，第一次遞迴運算可以提升1.5dB的效能，第二次運算與第一次運算比較，效能提升0.5dB，更多遞迴其效能提升的效果會越來越小，由此可知，Wimax-New的系統約3次遞迴即可有不錯的表現。

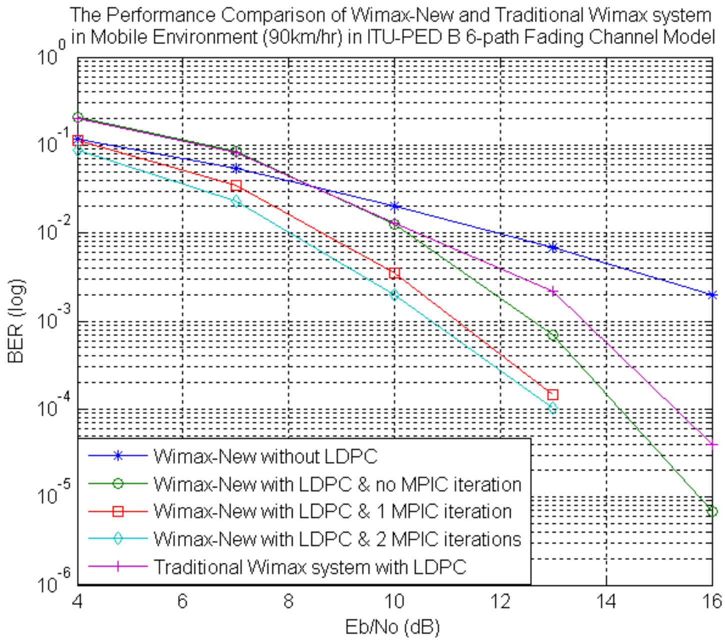

圖4-3 Wimax-New與傳統Wimax系統之比較
(車速90km/hr，編碼碼率1/2，模擬通道ITU PED-B 通道)

圖4-3為本系統Wimax-New與傳統Wimax系統在車速90km/hr的性能比較，由圖可以知道，傳統系統即使有使用LDPC碼保護，在高車速的情況下，系統效能一樣會減低，而本系統則仍可有穩定的表現。

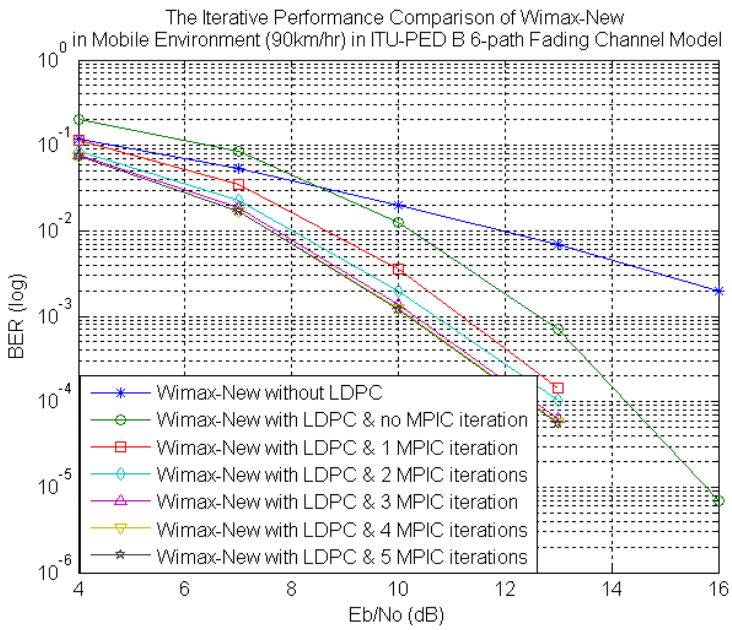

圖4-4 Wimax-New系統於不同遞迴訊號處理之性能比較
(車速90km/hr，編碼碼率1/2，模擬通道ITU PED-B 通道)

圖4-4為本系統設計於車速90km/hr的6路徑雷利衰變(Rayleigh fading)通道，在不同遞迴運算的效能比較，由模擬可以知道，因為有多路徑增益的物理現象保護，本系統即使在高車速的情況下，其系統效能仍有不錯的表現。

第五章　OFDM與CDMA系統效能分析

隨著最近這幾年無線通訊的發展，高速率傳輸在各領域的應用也越來越多，所以高容量和高涵蓋率的需求也越來越高。在過去二十年當中，CDMA一直扮演第三代行動通訊的核心，隨著第三代行動通訊的普及下，目前研究逐漸朝向第四代行動通訊的發展。以OFDM為基礎的OFDMA多重接取技術已是實現第四代行動通信系統的關鍵技術，目前兩大第四代行動通信系統標準(i.e., 3GPP LTE-A Long Term Evolution- Advanced及Mobile WiMAX 2) 的下行都採用OFDMA技術。

在本章節中，我們將兩種調變技術－正交分頻多工(OFDM)與直接序列展頻分碼多工(DSSS－CDMA)，應用在蜂巢式行動通信下行系統中。針對OFDM系統，我們使用強制歸零等化器來還原訊號。針對CDMA系統，我們使用四種在頻域上的等化器來降低使用者間的干擾。

蜂巢式系統藉由在空間上重覆使用相同的頻道來達到較高的系統容量，但這也導致了同頻干擾問題的產生。我們使用電腦模擬來比較以上兩種調變方式在蜂巢式環境下的訊雜比(SIR)和錯誤率。由於我們的系統是模擬是在蜂巢式環境下進行，所以我們也考慮了無線電傳輸通道的路徑損耗(path loss)與遮蔽(shadowing)效應。

5.1 OFDM系統傳輸模型

首先先介紹正交分頻多工OFDM的系統，OFDM的概念就是將資料用彼此成正交的載波做傳輸，故OFDM也可視為是窄頻的訊號。而OFDM也可達到高傳輸的特性，其傳送端的模型架構，如下圖所示：

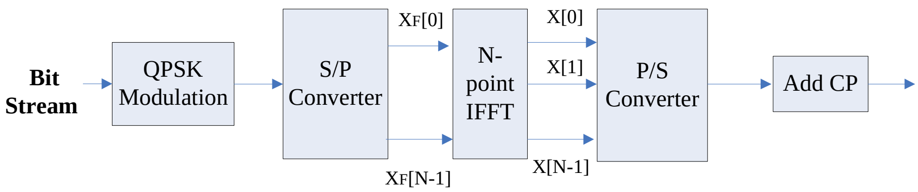

圖5-1 OFDM傳送端模型

將我們的資料串做QPSK的調變之後，將串連的訊號轉換成平行的訊號，再針對每個bit做點對點的IFFT轉成時域上的訊號，再轉回串連的訊號後，最後加上cyclic prefix(CP)傳送出去。加上CP的目的是當訊號通過多路徑的通道下，避免產生訊號之間的干擾，而破壞了OFDM每個載波的正交性。

當訊號傳送到通道之後，就設計了接收端的模型架構，如下圖所示：

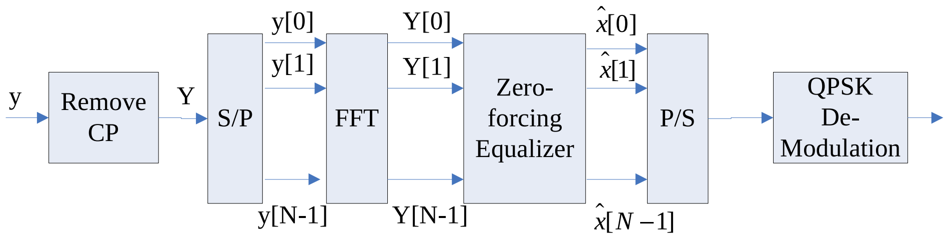

圖5-2 OFDM接收端模型

當我們接受到訊號後，首先先移除CP之後再來做處理。將串連的訊號轉成平行的訊號之後，做點對點的FFT轉成頻域上的訊號再來做處理，將每一個載波經過強制歸零等化器(Zero-forcing Equalization)後，再轉回串連訊號後，最後再解回我們所要的訊號。關於強制歸零等化器可以由下列敘述所表示：

The Zero-forcing equalizer can be realized as a linear equalizer with G[n] at the n-th subcarrier.

$$G[n] = \frac{H^*[n]}{|H[n]|^2}$$

$$x[n] = G[n]Y[n] = \frac{H^*[n]}{|H[n]|^2}Y[n] = \frac{Y[n]}{H[n]}$$

強制歸零等化器的優點為低複雜度且低成本，它的概念是欲將通道對訊號的影響降到最低，並且將訊號還原，而缺點為有雜訊放大的問題。

5.2 DSSS-CDMA系統傳輸模型

接下來介紹的是直接序列展頻分碼多工(DSSS-CDMA)的系統，CDMA的概念是訊號使用相同的頻率和時間一起傳送，但是乘上不同的碼做為區分，其傳送端的模型如下圖所示：

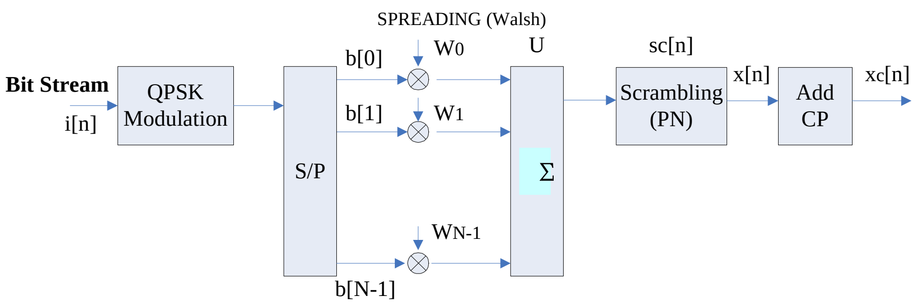

圖5-3 CDMA傳送端模型

將我們的資料串做QPSK的調變之後，將串連的訊號轉換成平行的訊號，再針對每個bit乘上各自的展頻碼(華式正交碼)，將所有展頻後的訊號全部加起來後，再乘上攪亂碼(PN序列)，攪亂碼的目的為跟其他Cell來的訊號的區分，為了跟OFDM比較的公平性，使得訊號長度相同，最後加上cyclic prefix(CP)傳送出去。

當訊號傳送到通道之後，就設計了接收端的模型架構，如下圖所示：

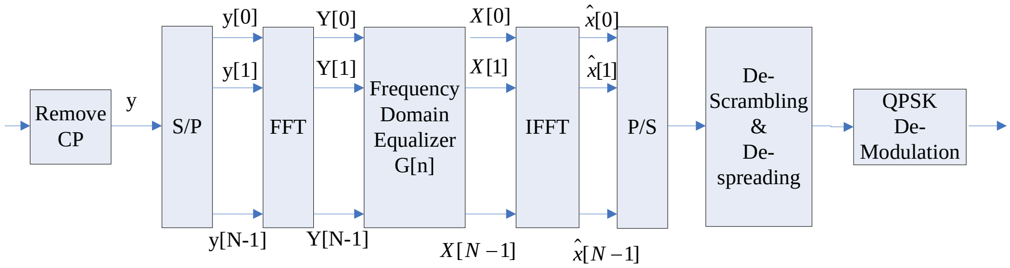

圖5-4 CDMA接收端模型

當我們接受到訊號後，首先先移除CP之後再來做處理。將串連的訊號轉成平行的訊號之後，做點對點的FFT轉成頻域上的訊號再來做處理，將每一個載波經過四種頻域等化器後，先轉回時域上訊號再將攪亂碼與展頻碼解回來，最後再解回我們所要的訊號。關於四種頻域等化器可以由下列敘述所表示，根據不同的頻域等化器，我們可以得到不同的結果。

1. MRC (Maximum ratio combination) :

$$G_{MRC}[n] = H^*[n]$$

2. EGC (Equal gain combination) :

$$G_{EGC}[n] = \frac{H^*[n]}{|H[n]|}$$

3. ZF (Zero forcing equalizer) :

$$G_{ZF}[n] = \frac{H^*[n]}{|H[n]|^2}$$

4. PEC (Partial equalization combination) : 這邊我們取 ß=0.6

$$G_{PEC}[n] = \frac{H^*[n]}{|H[n]|^{1+\beta}} \quad , \ -1 \le \beta \le 1$$

5.3 模擬假設

而我們收到的訊號會經過三種衰減，第一種為傳送端和接收端之間的距離造成的路徑損耗(path loss)，第二為因為地形環境所造成的遮蔽效應(shadowing)，第三為因為多重路徑的關係所形成的衰減(small-scale shadowing)。我們可以將通道模型化為：

$$h(t) = P\sum_{j=1}^{L} a_j e^{j\theta_j}\delta(t-\tau_j)$$

其中的參數分別為:

P: 平均訊號功率（受到shadowing和 path loss的影響）

a_j: 第j-th路徑的路徑強度（Rayleigh distributed）

θ_j: 第j-th路徑的路徑相位（Uniform distributed）

τ_j: 第j-th路徑的路徑延遲

L: 所有路徑的數目

我們的環境參數設定為：

Cellular Environment	**Parameters**
Cell radius	1000 (in meters)
Number of co-channel cells	18
BS transmitter power	0 dBW
Front-to-back ratio of the BS antennas	30 dB
Cluster size	1,3
Path loss exponent	4
Shadowing std deviation	8 dB
Antenna	Omni, 120º sector, 60º sector
path	2, 4
Relative power	[0 0] , [0 0 0 0] dB
Amplitude	Rayleigh fading
OFDM / CDMA	**Assumptions**
Bandwidth	2 MHz
Subcarrier spacing	15 kHz
FFT size	128
CP size	32
Modulation	QPSK
Walsh code length	128
PN sequence register length	22
PN sequence polynomial	$1+x^{22}$

5.4 模擬結果與討論

由圖5-5及5-6實驗結果我們可以觀察出在滿載時(full-load)，周圍有18個Co-channel cells(考慮2層的Co-channel cells)，不論是在2-path或是4-path的情形，系統效能都是CDMA比OFDM來的好。雖然CDMA會有比較嚴重的MAI的問題，但是對抗外面干擾的能力還是比OFDM來的好。

當我們接受的天線使用有方向性的時候，也可以有效的濾掉其他cell來的干擾，也可以降低錯誤率。

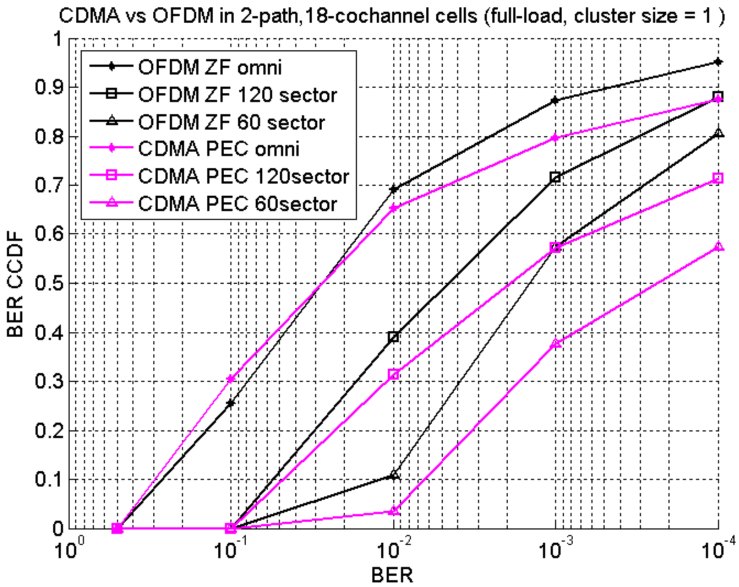

圖5-5 CDMA與OFDM在2-path且full-load情況下之效能

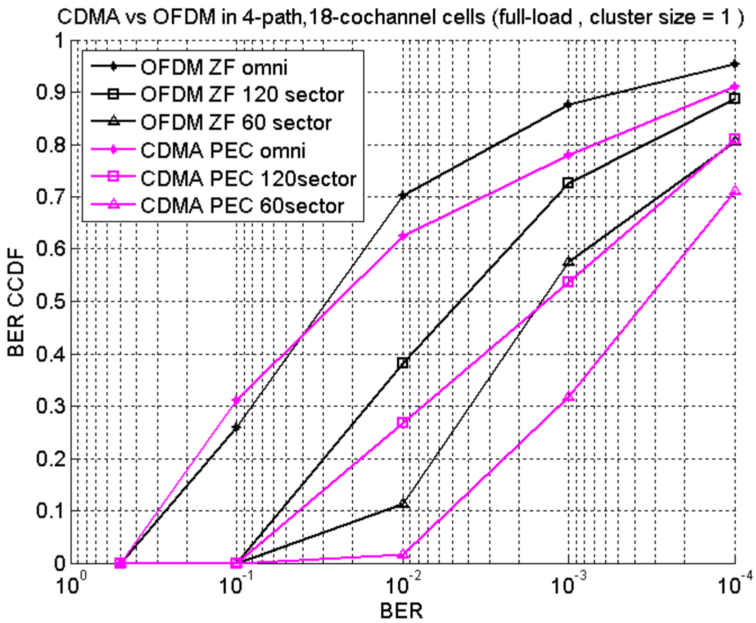

圖5-6 CDMA與OFDM在4-path且full-load情況下之效能

由圖5-7及5-8實驗結果我們可以觀察出在使用120°方向性天線，周圍有18個Co-channel cells(考慮2層的Co-channel cells)的環境下，不論是在2-path或是4-path的情形，當負載(loading)不同時，系統效能都是CDMA比OFDM來的好。雖然OFDM本身內部彼此正交，不會互相干擾；而CDMA有MAI的問題，但是使用PEC等化器可以有效消除部分的MAI問題。尤其是當負載降低的時候，在4-path的情形，CDMA的系統效能比OFDM來得佳。

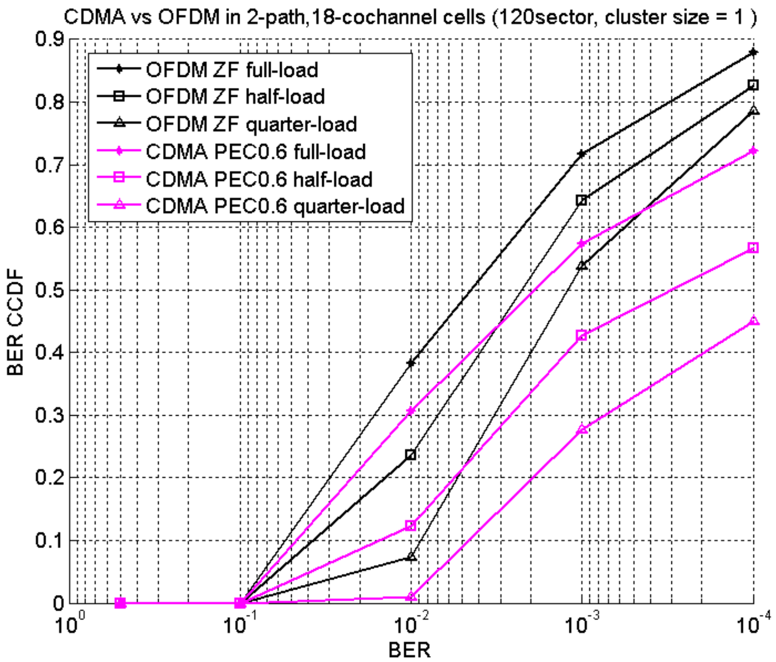

圖5-7 CDMA與OFDM在2-path且3-sector情況下之效能

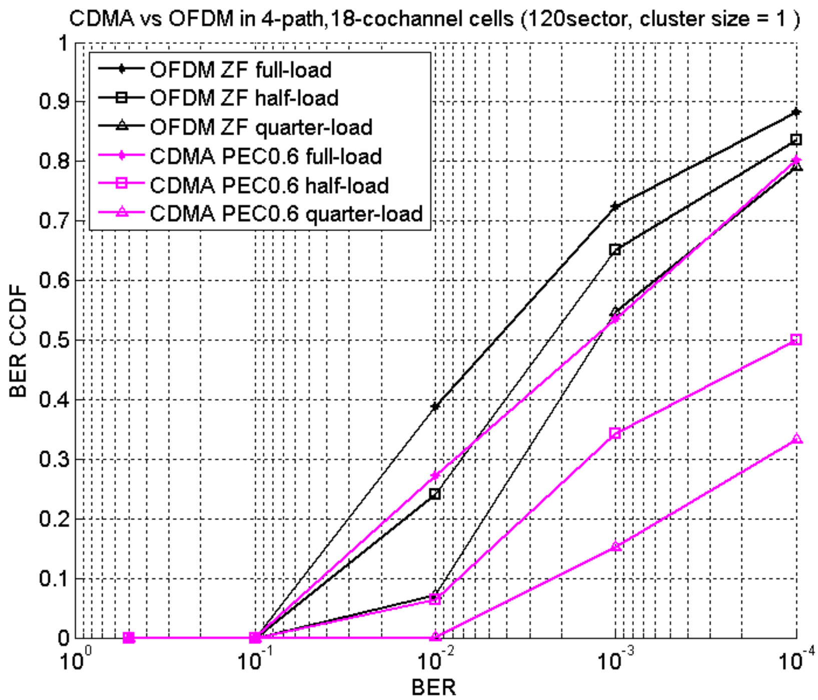

圖5-8 CDMA與OFDM在4-path且3-sector情況下之效能

第六章　應用干擾協調技術之OFDMA下行系統效能分析

正交分頻多工(Orthogonal frequency division multiplexing, OFDM)是廣泛用於寬頻無線通訊系統裡的一種傳輸技術；OFDM不僅為調變之用，更是可延伸至多重擷取技術，稱之為OFDMA，是未來行動通訊系統中增加頻譜效率(spectral efficiency)最好的多重接取方法。許多通訊標準，如：3GPP(3rd Generation Partnership Project)的LTE(Long Term Evolution)、3GPP2 (3rd Generation Partnership Project 2)的UMB(Ultra Mobile Broadband)和Mobile WiMax(Worldwide Interoperability for Micro Access)等，皆使用OFDMA為其下行(downlink, DL)傳輸技術[1]－[3]。因為OFDMA具有細胞內正交性(intra-cell orthogonality)之故，其主要的干擾來自細胞間干擾(inter-cell interference)，尤其對於頻率再利用因子(frequeny reuse factor)為１的OFDMA系統之細胞邊緣用戶影響最為嚴重。

為了在整個蜂巢式系統中有均勻的使用者生產量(uniform user throughput)，inter-cell interference是系統效能主要的限制因素，因其會產生較低的位元率(bit rate)，故此，對於蜂巢式系統中邊緣使用者而言，發展對抗細胞間干擾(inter-cell interference mitigation, ICIM)的方法便極其重要。

為了解決干擾的問題，許多Pre-4G 系統，如 3GPP的LTE、3GPP2的UMB與Mobile WiMax等，皆使用inter-cell interference coordination(ICIC)作為干擾消除的方法；ICIC的共通點是在上行(Uplink, UL)與下行(Downlink, DL)的資源(時間、頻率、傳送功率等)使用上作限制；此法為避免嚴重的inter-cell interference提供了一條路，提供所有使用者更平衡的位元率；很多ICIC的方法已被提出，如：partial frequency reuse(PFR)[5, 6]、soft frequency reuse[7, 8]、inverted frequeny reuse[9]等，其中3GPP LTE、Mobile WiMax與UMB均支援PFR。

為了增加3G(3rd generation)的分碼多重擷取系統(Code division multiple access, CDMA)中cell邊緣的無線電覆蓋(radio coverage)面積，利用巨分集(Macro diversity)技術的軟性換手(Soft handover, SH)方法已經被使用來正視蜂巢式系統間干擾的問題；不僅如此，CDMA中的處理增益(processing gain)也能減輕cell-edge的干擾問題。為了維持一個簡化的無線電存取網路(Radio access network, RAN)架構，大家都同意SH不會存在3GPP LTE裏。儘管如此，SH仍然被IEEE 802.16e-2005視為一選擇性的選項，又被稱為巨分集換手(macro diversity handover)[3]。

傳統上，頻率再利用的方法用於OFDMA中，而SH則用於CDMA中。在本章中，我們提出一種用於OFDMA DL中的混合式ICIM方法，此種方法同時使用了PFR與SH；模擬結果顯示此種混合式方法能讓整個系統增加一些容量(capacity)，同時改善蜂巢式系統中邊緣使用者(cell edge user)的訊號品質。

6.1 部分頻率再利用

為了最大化頻譜效率，現今的OFDMA系統，如3GPP的LTE、3GPP2的UMB與Mobile WiMax，皆假設頻率再利用因子(Frequeny reuse factor, FRF)為１；雖然此假

設的生產量(throughput)最大，但卻為蜂巢式系統中邊緣使用者(cell edge user)帶來較低的訊號品質。一種比較實際的作法，是在sector為三的蜂巢(cell)中使用PFR，此法降低了蜂巢式系統間的干擾，但是亦減少了一個蜂巢中可使用的頻率資源。在現今的OFDMA系統中，為了符合sector為三的蜂巢架構，FRF通常為一或三；對於CDMA的系統，因為正交展頻碼能提供處理增益以抵抗蜂巢式系統間干擾，故PFR正常都為1。

PFR是一種在細胞間限制頻率資源使用的蜂巢式系統間協調(inter-cell coordination)的機制，其想法乃是將整個頻帶分成兩個部份，稱之為F_1和F_3，而F_3再進一步分割為三段：F_{3A}、F_{3B}、F_{3C}，故可得四個正交的子頻帶(subband)，參見圖一；在不失一般性的前提下，假設各子頻帶擁有相同的頻寬(bandwidth)。F_1被稱為細胞中央頻帶(cell center band)，其FRF(Frequeny reuse factor)為1，只被細胞內部的用戶所使用；F_3則稱為細胞邊緣頻帶(cell edge band)，FRF值為3，細胞邊緣用戶(cell edge user)被限制使用此頻帶；儘管如此，若細胞邊緣頻帶未完全佔滿，細胞內部的用戶便可使用此頻帶。

等效再利用因子(Effective reuse factor, ERF) r_{eff} [11]定義為全部可使用之頻寬與在每一個細胞內實際使用的頻寬比例，數學式為：

$$r_{eff} = BW_{all} / BW_{cell} = (BW_{F1} + BW_{F3}) / (BW_{F1} + (1/3)*BW_{F3}) \quad (6\text{-}1)$$

其中BW_{all}為全部可使用的頻寬，BW_{cell}為每一個細胞內實際使用的頻寬。

在本章中，我們假設每一個細胞皆傳送其最大的功率(maximum transmitsion power)，且為定值，並傳輸的功率頻譜密度為對水平軸為定值(a flat transmission power spectrum density)，圖6-1顯示了在sector為三的蜂巢(tri-sector cell)中頻譜使用的概念；其中亦與單純的reuse-1做比較，吾人可知r_{eff}為α/β。

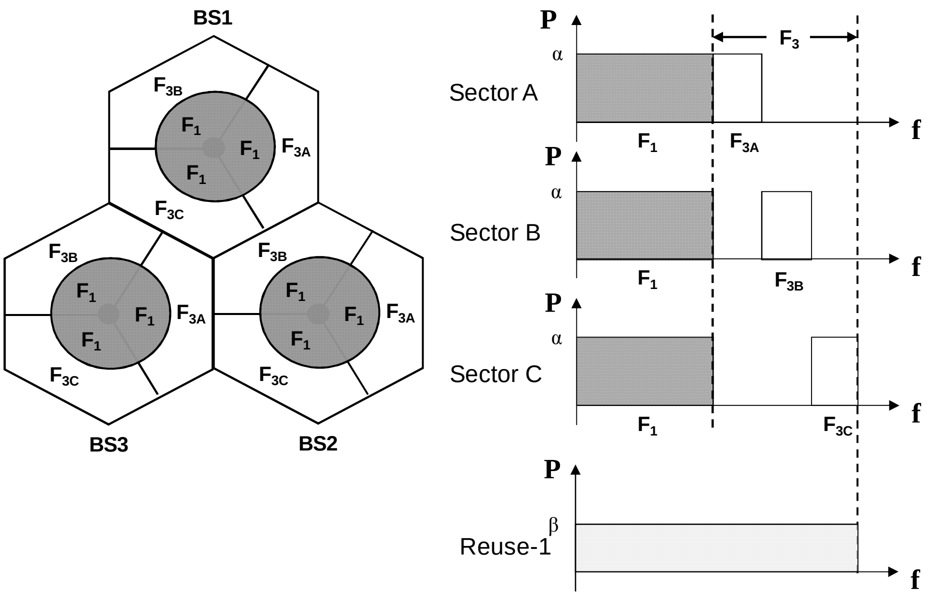

圖6-1 sector為三的蜂巢式系統中頻譜設置情形

6.2 軟性換手

在3G CDMA系統中，下行的巨分集(Macro diversity)技術中最主要用的就是SH(Soft handover)，對降低蜂巢式系統間的干擾(inter-cell interference, ICI)的確是很好的對策；當SH開始時一個使用者(User equipment, UE)同時間和數個細胞連結，構成一個活動組(active set)，其包含現正使用中的細胞(通常為傳輸品質最好的細胞)與所有符合SH條件的細胞[12]，這與強制換手(hard handover)不同，其活動組內只有一個細胞。在SH下，一個UE會同時收到多個細胞送來相同頻帶的訊號，益處在於原來的視為干擾的訊號，現今轉為理想的訊號(desired signal)，可大大增進細胞邊緣使用者的傳輸品質。

軟性換手所需的額外消耗(overhead)[12]是一項重要指標來量化在一個網路中軟性換手的情形，它被視為衡量傳輸時所需的額外資源。請注意，大的overhead意味著需要大量的控制信號，導致降低了系統容量。軟性換手所需的消耗(overhead)η定義為：

$$\eta = \sum_{n=1}^{N_{MAS}} n \cdot P_n - 1, \qquad (6\text{-}2)$$

其中 N_{MAS} 為最大活動組(maximum active set)的大小， P_n 為在n-way下SH的使用者(User equippment, UE)機率，本章中，1-way SH意思為一個UE只和一個細胞連接，2-way SH為一個UE只和兩個細胞連接，依此類推。

6.3 混和系統概念

分割細胞邊緣及內部使用者

一個被廣泛接受的方式來分割的UE是根據幾何因子(G-factor)。 G-factor是一個 UE的領航子載波(pilot subcarriers)在頻譜F_1所量測到的寬頻平均信號干擾加雜訊功率比（Signal to interference plus noise ratio, SINR）。然後G-factor與預先定義的閾值(threshold)比較，以確定UE是否為細胞內部用戶(Cell interior user, CIU)或細胞邊緣用戶(Cell edge user, CEU) [10] [13] [14] [15]，這是因為細胞邊緣用戶的SINR總有明顯的衰減。一個UE的平均SINR的定義為自己所收到的全部訊號功率與其他細胞的干擾加雜訊功率的比值。應該指出的是，SINR是根據短期衰落(short-term fading)來平均，但不是對遮蔽(shadowing)來平均。在本章中，我們考慮一個細胞邊緣的UE必須用一種ICIM的方法來保護。例如：通過reuse-3或軟性換手的方法，若在UE所測量的G-factor小於0分貝的閾值 [13] [15] [16]；否則，UE就被視為細胞內的用戶。

問題描述

我們考慮了有PRF的OFDMA下行系統，並且有提供SH(Soft handover)的功能。假設一個 UE是一個細胞邊緣用戶且超過一個以上的可用細胞待換手(handover)。換手清單(handover list)是列出其鏈結品質(link quality) 滿足了SH的要求的細胞，

因此在清單中的每一個細胞便可以加到活動組(active set)。請注意，主要服務細胞(serving cell)無疑也在換手清單中，故換手清單中的細胞數總是大於或等於一。在這種情況下，下行OFDMA的系統可以使用以下兩種方法傳送預定的資料給 UE：第一種方法是基於SH，OFDMA下行系統從UE活動組中的所有細胞使用屬於reuse-1的F_1子通道(subchannel)，發送資料給UE，我們稱此為法A；第二種方法是基於PFR，OFDMA 下行系統從主要服務細胞使用該細胞中屬於 reuse-3 的子通道(subchannel)，即F_{3A}、F_{3B}、或F_{3C}，傳送資料給UE，。我們稱此為法B；注意，在法A中，活動組正是在換手清單中的所有細胞，而在B方案中，活動組只有主要服務細胞。

在上述情況下，剩下的兩個問題為：1)哪些方法(法A或法B)可以為 UE提供較高的信號干擾加雜訊功率比(SINR)？ 2)與標準PFR相比，即無軟性換手，是否可以藉者動態選擇法A和法B來獲取生產量的增益(throughput gains)呢？這兩個問題將探討如後。

<u>PR及SH的混合系統</u>

為了提高細胞邊緣的位元率(bit rate)和整個系統的容量，我們開發一個ICIM的方法，其根據能提供較好的信號品質(較高的SINR)的方法，動態在法A和法B中選擇。對於標準的PFR，主要服務細胞首先根據UE的G-fator將UE分為CIU或CEU兩類。如果G-factor大於預先定義的閾值（例如，0分貝）UE就被視為細胞內部用戶(CIU)，主要服務細胞(serving cell)便將該UE的資料通過子通道的reuse-1子頻帶(subband)發送給該UE；否則該UE會被歸類到細胞邊緣用戶，便將該UE的資料通過子通道的reuse-3子頻帶發送給該UE，即使用法B。

圖6-2顯示了所提出混合方案(hybrid scheme)的運作流程圖。對於所提出的方法，細胞邊緣用戶或許被分配到不是reuse-3的子通道就是配合軟性換手的reuse-1子通道。我們注意到，CIU的運作與標準的PFR和所提出的混合方案均相同。當一個UE被歸類為細胞邊緣用戶，如果只有一個細胞在UE的換手清單(handover list)裏，則主要服務細胞會用法B將資料傳給該UE。另一方面，若UE的換手清單的細胞數大於一，則主要服務細胞會動態地選擇法A或法B將資料傳輸給該UE，選擇的標準是根據信號的品質，可表為：

$$\begin{aligned}&\textit{If}\ \ \gamma_A^{(1)} > \gamma_B^{(3)},\ \textit{choose Scheme A;}\\&\textit{otherwise, choose Scheme B.}\end{aligned} \qquad (6\text{-}3)$$

其中$\gamma_A^{(1)}$及$\gamma_B^{(3)}$為在法A和法B下，UE所量到的SINR，上標y為使用reuse-y的子頻帶。

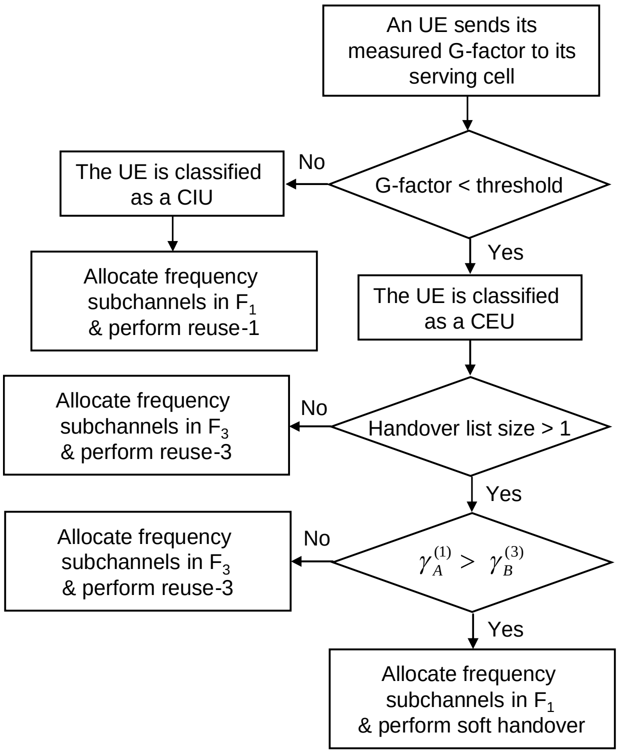

圖6-2 混合方案(hybrid scheme)的運作流程圖

6.4 系統模型

PFR可藉著靜態(static)或動態(dynamic)的調整(coordination)來達成。由於動態的調整引入了大量的overhead和排程的複雜度(scheduling complexity)，故在[17][18]中建議使用靜態的調整。在這份報告中，只考慮靜態的調整。

下行的平均SINR模型的建立

在我們的SINR計算哩，不考慮快速衰落(fast-fading)，並假設系統只受傳輸損耗(Propagation loss, PL)和對數常態分佈(log-normally distribution) 遮蔽(shadowing)。我們進一步假設主要服務細胞(serving cell)是一個包含路徑損耗(path loss)、遮蔽衰落(shadow fading)、及天線增益(antenna gain)後，所接收到信號最強的細胞。

假設指定給每個細胞的所有子通道均被使用，即滿載系統(fully loaded system)，並假設相同的發射功率P_T，則發射功率頻譜密度(transmission power spectrum density, TxPSD) P_t 定義如下式：

$$P_t = P_T / BW_{all} \cdot r_{eff} (= P_T / BW_{cell}) \tag{6-4}$$

因此，對一個不使用SH(soft handover)的UE而言，其平均的SINR可以寫為：

$$\gamma^{(x)} = \frac{P_t \cdot L_s \cdot S_s \cdot A_s}{\sum_{i \in \Phi_x} P_t \cdot L_i \cdot S_i \cdot A_i + P_N},\ (x = 1, 3) \qquad (6\text{-}5)$$

其中L_j、S_j、及A_j為從細胞j到UE中的路徑損耗(pathloss)、遮蔽衰落(shadow fading)和天線增益，下標s和i代表主要服務細胞(serving cell)和干擾細胞(interfering cell)，Φ_1和Φ_3分別是reuse factor為1和3的干擾細胞集合，P_N表示收到的雜訊功率頻譜密度。

此外，當 UE處於SH時，其平均的SINR可以表示為：

$$\gamma_A^{(1)} = \frac{\sum_{s \in \Phi_{AS}} P_t \cdot L_s \cdot S_s \cdot A_s}{\sum_{i \in (\Phi_1 - \Phi_{AS})} P_t \cdot L_i \cdot S_i \cdot A_i + P_N}, \qquad (6\text{-}6)$$

其中Φ_{AS}為UE的活動組(active set)；為了計算式(6-3)，我們發現，$\gamma_A^{(1)}$可直接從(6-6)計算，$\gamma_B^{(3)}$可以將x = 3帶入式(6-5)而得到。

鏈結頻譜效率的評估

根據Shannon的容量公式[19]，從基地台(BS)到一個特定的用戶(user)可達到的鏈結頻譜效率的C (bps/Hz)是接收SINR之平均的函數。

假設其他細胞的干擾可以模擬為AWGN，並且我們不考慮在接收端其他細胞的干擾消除技術，修改過的Shannon公式[20] 在蜂巢式行動通信系統能計算鏈結容量。此公式如下：

$$\tilde{C}(\gamma) = \xi \cdot \log_2(1 + \gamma / \varsigma) \text{ bps/Hz} . \qquad (6\text{-}7)$$

其中ξ、ς及γ為系統頻寬效率、SINR實現效率(implementation efficiency)與接收SINR的平均。對於典型的城市(Typical Urban, TU)通道模型和單輸入單輸出(Single-Input Single-Output, SISO)的天線架構，模擬顯示[20]，公式(6-7)中的$\xi = 0.56$及$\varsigma = 2$，能符合3GPP LTE的鏈路容量效能。因此，我們採用修改後的Shannon容量公式，設定參數$\xi = 0.56$及$\varsigma = 2$，來計算鏈結頻譜效率(link spectral efficiency)。

系統容量估計

我們假設用戶均勻地分佈在細胞的覆蓋範圍內，且在下行(DL)時有無限的傳輸流量。此外，假設在細胞中心及邊緣頻帶使用 Round Robin(RR)排程。在使用 RR排程下，系統容量 T 可以計算為[20,21]：

$$T = BW \cdot v \cdot \int \tilde{C}(\gamma) f_\gamma(\gamma) d\gamma \qquad (6\text{-}8)$$

其中v稱作損失因子(loss factor)，為系統的消耗(overhead)；而$f_\gamma(\gamma)$是SINR的機率密度函數(probability density function, pdf)，BW是所配置的頻寬(bandwidth)。在本

章中，損失因子設為1;這會產生樂觀的結果，但被認為是可以接受來作為比較之用。

在一個滿載的系統，對CIU而言，幾乎不可能用到細胞邊緣頻帶(即F_3)，因此將局限於細胞中央頻帶(即F_1)。這會導致用戶群的分開，使得CIU只用細胞中央頻帶而CEU只用細胞邊緣頻帶。從式(6-8)，PFR架構下，平均的細胞內部容量($T_{Interior}$)和平均的細胞邊緣容量(T_{Edge})可以計算如下：

$$T_{Interior} = BW_{F_1} \cdot \int \tilde{C}(\gamma_I) f_{\gamma_I}(\gamma_I) d\gamma_I \, , \tag{6-9}$$

$$T_{Edge} = \frac{1}{3} BW_{F_3} \cdot \int \tilde{C}(\gamma_E) f_{\gamma_E}(\gamma_E) d\gamma_E \, , \tag{6-10}$$

下標 I 及 E 分別表示CIU和CEU用戶。

本章所提出的混合方案(hybrid scheme)，因為我們在細胞中央頻帶有使用Round Robin(RR)排程，用法A的CIU和CEU，在細胞中央頻帶都有相同的機會使用子通道。因此，細胞內的平均生產量(throughput)和細胞邊緣的生產量，可以計算如下：

$$T_{Interior} = BW_{F_1} \cdot \frac{P_I}{P_I + P_2 + P_3} \cdot \int \tilde{C}(\gamma_I) f_{\gamma_I}(\gamma_I) d\gamma_I \, , \tag{6-11}$$

$$\begin{aligned} T_{Edge} = & \frac{1}{3} BW_{F_3} \cdot \int \tilde{C}(\gamma_{E,B}) f_{\gamma_{E,B}}(\gamma_{E,B}) d\gamma_{E,B} + \\ & \sum_{n=2}^{3} \Big(\frac{1}{n} \cdot BW_{F_1} \cdot \frac{P_n}{P_I + P_2 + P_3} \cdot \\ & \int \tilde{C}(\gamma_{E,A,n}) f_{\gamma_{E,A,n}}(\gamma_{E,A,n}) d\gamma_{E,A,n} \Big), \end{aligned} \tag{6-12}$$

其中P_I是指CIU的機率(CIU佔所有用戶的比例); P_n是指在n-way SH下的使用者機率(n-way SH下的使用者佔所有用戶的比例);下標A和B分別代表法A和法B使用者。請注意，(6-12)式中右手邊的$1/n$ ，代表n-way SH下所導致的容量損失因子(loss factor)。在本章中，我們假設最大的活動組為3個細胞($N_{MAS} = 3$)[22]，及add_threshold為4分貝(Window_add = 4分貝)[22]。

在獲得細胞內部用戶和細胞邊緣用戶的平均生產量時，平均的細胞生產量T_{Cell}便為：

$$T_{Cell} = T_{Interior} + T_{Edge} \, . \tag{6-13}$$

<u>*模擬方法與模擬參數*</u>

模擬的假設和參數基本上遵循3GPP的評估標準[10]。可用的下行頻寬固定在 10兆赫(MHz)。我們考慮由19個基地台(Base station, BS)所組成的多細胞系統(multi-cell system)。一個BS掌控三個sectors，即全部有57個sectors。無線電鏈結是

受和距離相關的路徑損耗(path loss)和對數常態遮蔽衰落(log-normal shadowing fading)。我們假設和距離相關的路徑損耗的傳輸損耗指數(propagation loss exponent)為3.76且對數正態分佈的標準差為8分貝。天線的型態取自文獻[10]。所有的模擬結果來自中心的BS，換言之，其餘的54個sectors為細胞間的干擾。表6-1列出了主要的模擬參數。

Parameters	Assumptions
Cellular layout	Hexagonal grid, 19 BSs, 3 cells per BS
Carrier Frequency	2 GHz
System bandwidth	10 MHz
Antenna pattern	As described in [10]
BS total Tx power	46 dBm
Site to site distance	1732 m
Distance dependent path loss	$128.1+37.6\log_{10}(R)$ (R: in km)
Minimum distance between UE and cell site	35 m
Penetration loss	20 dB
Shadowing standard deviation	8 dB
Shadowing correlation between BSs / sectors	0.5 / 1
BS antenna gain	14 dBi
UE antenna gain	0 dBi
UE noise figure	9 dB
Antenna configuration	1 x 1

表6-1 模擬參數

6.5 模擬結果與討論

模擬結果是建構在標準的部分頻率再利用(PFR)和所提出的混合方案(hybrid scheme)。此外，我們考慮等效再利用因子(Effective reuse factor, ERF) r_{eff}的值介於1.1和2之間。請注意，在細胞邊緣頻帶配置大量的子通道會導致在每個細胞內頻寬利用率有很大的損失。因此，我們限制ERF為2，等於保留3 / 4的頻率資源給細胞邊緣頻帶F_3。

首先，了解在模擬系統中CIU和CEU所佔的百分比是重要的資訊。對於整個細胞下行G-factor，針對r_{eff} = 1.2、1.5和1.8的累積分佈函數(cumulative distribution function, CDF)繪於圖6-3。在閾值是0分貝時，可以發現，在細胞內CEU所佔的比率約34%，CIU約 66%。此外，由於我們假設BS間的距離為1732公尺(見表6-1)，因此本模擬是干擾限制(interference limited)的系統；故此，可以發現，對於不同的ERF而言，CDF的趨勢幾乎沒有改變。

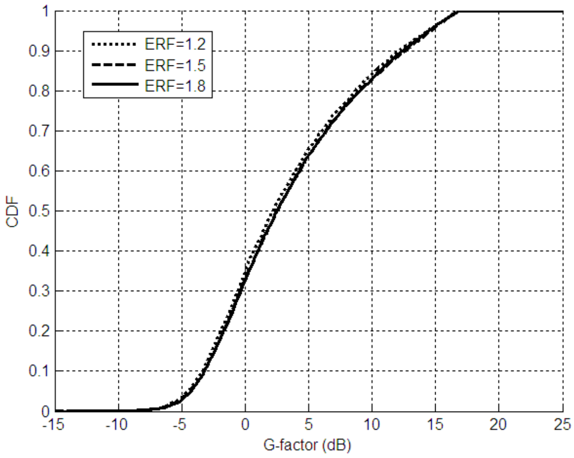

圖6-3 整個細胞的G-factor分佈

軟性換手消耗的估計

在此，我們研究所提出的混合方案的軟性換手消耗η。為了可行性的關係，混合方案中的一個重要的要求是，與當前的3G CDMA系統相比，要有低的軟性換手消耗。表6-2顯示了在n-way軟性換手中UE的機率。將模擬結果帶入式(6-2)，我們發現，軟性換手的消耗約為0.15。眾所皆知的是，在標準的WCDMA網路中，軟性換手的消耗約0.2 ~ 0.4 [12]；除此之外，在人口密集的城市地區，WCDMA網路的平均軟性換手消耗為0.38 [12]。因此，我們的方法所導致的軟性換手消耗相對較小。

# of SH Branches	n =1	n=2	n=3
P_n	~0.91	~0.03	~0.06

表6-2、在n-way軟性換手中UE的機率

平均SINR的比較

給定一個換手清單(handover list)內有兩個以上細胞的CEU，其用n-way軟性換手(即法A)所得的SINR大於使用reuse-3(即法B)的機率可寫為

$$P(n) = P(\gamma_A^{(1)} > \gamma_B^{(3)} \,|\, N_{AS} = n), \quad (6\text{-}14)$$

其中N_{AS}代表該使用者活動組的大小。

我們在不同的ERF的模擬結果如圖6-4所示。可以觀察到P(2)介於0.14和0.20之間及P(3)介於0.62和0.70之間。因此，我們得出結論，軟性換手細胞數目增加，*P(n)* 亦會隨之增加。

在換手清單(handover list)的大小大於一之下，CEU平均SINR的分佈如圖6-5所示。模擬結果顯示，用混合的方案所得到的平均SINR，與標準PR相比，平均而言，增加了約1.8分貝。與表6-2做連結，我們得出這樣的結論：全部使用者數的9%(P_2+P_3)

用戶或是CEU的26%((P_2+P_3)/P_E)，在本章的方法下，SINR將獲得改善，相對的增益，平均增加約1.8分貝。

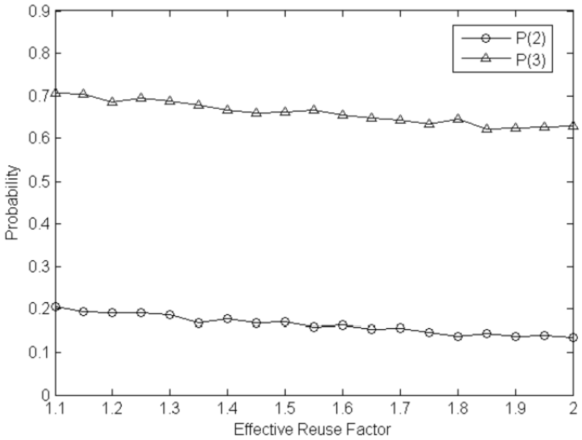

圖6-4 *P(n)* 對ERF的反應

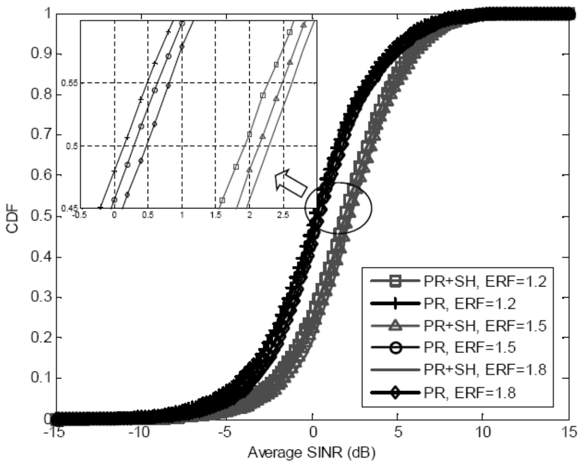

圖6-5 CEU平均的SINR分佈

<u>*鏈結頻譜效率的比較*</u>

更有意義的指標，是鏈結頻譜效率(spectral efficiency, SE)的改善程度，藉著從軟性換手及reuse-3的方法所導致的頻寬損失來觀察。鏈結頻譜效率改善的條件可表為

$$\frac{1}{n}\cdot\log_2(1+\gamma_A^{(1)}/\varsigma)>\frac{1}{3}\cdot\log_2(1+\gamma_B^{(3)}/\varsigma)\,, \qquad (6\text{-}15)$$

其中n表示軟性換手細胞的個數。對於使用2-way或3-way軟性換手的細胞邊緣UE，$\gamma_A^{(1)}>\gamma_B^{(3)}$ 意味著式(6-15)需成立，從而導致鏈結容量(link capacity)的提高。為了獲得鏈結容量的改善，我們進一步定義有效鏈結頻譜效率(effective link SE)：

$$\tilde{C}_{eff}(\gamma)=\frac{1}{m}\tilde{C}(\gamma)\,, \qquad (6\text{-}16)$$

其中m是頻寬損失因子(bandwidth loss factor)，與reuse-3方法(m = 3)或軟性換手方法(m = 2或3)有關。對於CIU，損耗因子則為1。

針對3GPP LTE而言，CDF在5％點的連結鏈結頻譜效率(又稱為5%使用者頻譜效率)，即95％的覆蓋率，是一個重要的標準，作為不同ICIM方法[10] [21] [23]的性能評估。因此，我們採用此一標準作為效能比較的指標。圖6-6顯示了 r_{eff} = 1.2，1.5，1.8的有效鏈結頻譜效率的分佈，特別是我們觀察低使用者頻譜效率的區域。從圖中我們觀察到混合方案的5％使用者鏈結頻譜效率約標準PR方法的1.3倍。

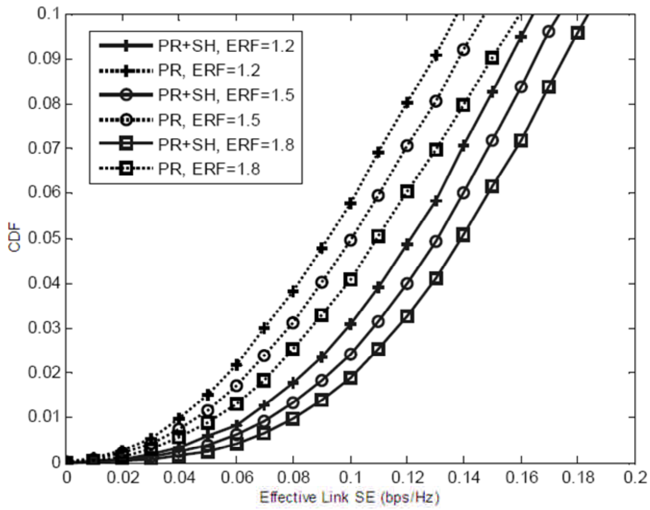

圖6-6 有效鏈結頻譜效率的分布

系統容量比較

圖6-7顯示了在不同ERF下，標準PR方法與混合方案的細胞平均生產量T_{Cell}、細胞內部的生產量$T_{Interior}$和細胞邊緣的生產量T_{Edge}。從這個圖中我們觀察到以下三點，首先，越大的ERF，導致越小的細胞平均生產量；這是由於ERF的增加，在每個細胞的可用頻寬就會減少，產生較低的頻率資源使用率。其次，混合方案提供了可觀的細胞邊緣的生產量增益，比PR方法多約18-92％，尤其當ERF減少時增益更顯著。第三，在相同的ERF下，與PR方法相比，混合方案造成約11-13％的細胞內部生產量的損失，進一步導致細胞總生產量的下降，特別當ERF小於於1.85時。這是因為在混合方案下，細胞中心頻帶F_1被所有的CIU和一些CEU所共享，因此分配給CIU的頻率資源，平均而言，低於PR方法。從以上的觀察，我們可以說混合方案是一個適當的方法來改善細胞邊緣的bit rate，並實現用戶之間的資料率(data rate)的公平性。

在無線通訊系統，用戶之間資料率的公平性是非常重要的考量。在這裡，我們定義了一個參數 f，稱為資料率公平指數(data rate fairnes index)：

$$\frac{T_{Interior}}{N_u \cdot P_I} = f \cdot \frac{T_{Edge}}{N_u \cdot P_E}, \tag{17}$$

其中N_u 表示在一個細胞內使用中的用戶數量，P_E 是CEU的機率。在這項研究中，我們考慮了三種資料率公平的情況[11]：第一個是f ＝ 1，被稱為所謂的公平，第二

種情況是f = 2，被稱為不公平，而最後一個是f = 3，稱為最不公平。在上述三種情況下，CEU的平均使用者生產量約為CIU的100%，50%和33.3%。

我們的模擬結果在不同資料率公平指數下的細胞平均生產量列於圖6-8。為了比較，我們也在圖中顯示單純reuse-1的結果。請注意，在reuse-1情況下，f的值是固定的，從我們的模擬結果顯示，約為 5.1。如圖6-8所示，在f = 5.1下，PR和混合方案皆勝過reuse-1。這一結果意味著，由PR及混合方案所造成損失頻寬的影響可以恢復，並進一步改善了生產量。從圖6-8，可以觀察到，與標準的PR方法相比，混合方案可在公平、不公平、和最不公平的情況下分別達到約 8%，5%和3%的平均細胞生產量增益。效能改進的原因解釋如下：由於考慮使用者間資料率的公平性，混合方案可以比標準的PR方法分配給用戶更均勻的生產量。換言之，混合方案能夠用較小的ERF來滿足給定的資料率公平指數。圖6-9顯示了資料率公平指數*f* 為ERF的函數。舉*f* = 1為例，PR方法和混合方案相對應的ERF分別為1.83和1.68。

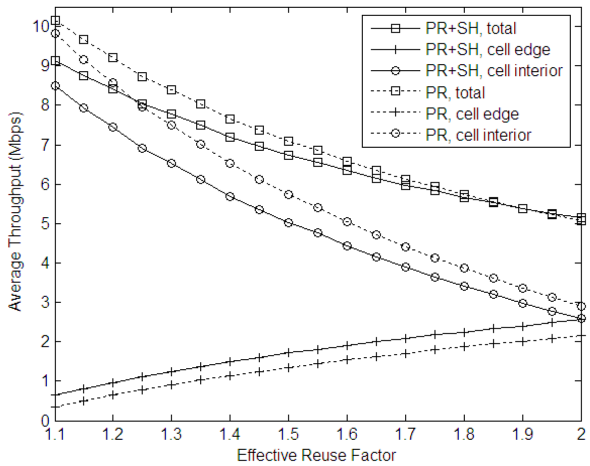

圖6-7 平均生產量

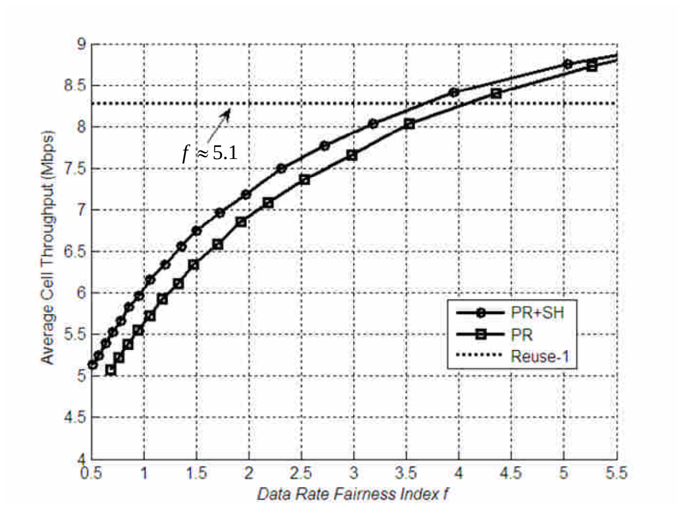

圖6-8 平均細胞生產量對資料率公平性的表現

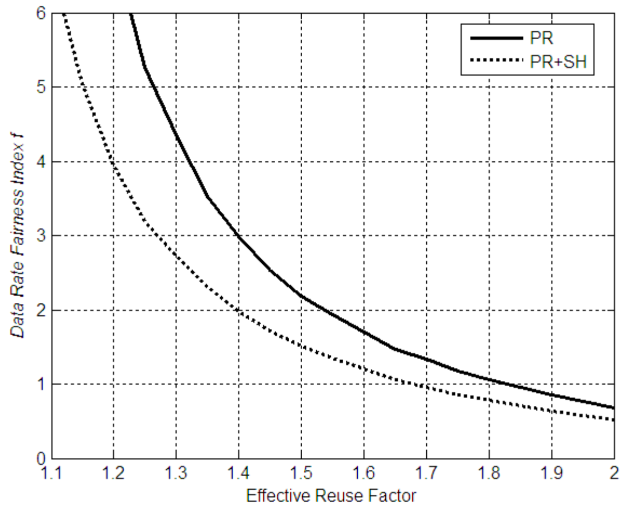

圖6-9 資料率公平性對ERF的表現

6.6 結論

在本章中，我們提出了一個多細胞OFDMA調變在蜂巢式系統間干擾消除(inter-cell interference mitigation, ICIM)的方法，我們特別針對下行(downlink, DL)傳輸作討論。所提出方法的基本想法是於部分頻率再利用(Partial frequency reuse, PFR)和軟性換手(Soft handover, SH)間動態作選擇，以提供蜂巢式系統中邊緣用戶較好的訊號品質。我們的模擬結果顯示，與標準的PFR相比，該方法有助於改善邊緣用戶的鏈結品質(link quality)和鏈結的頻譜效率。藉著使用我們的方法，有一個顯著的細胞邊緣的生產量(cell edge throughput)增益及較低的軟性換手(soft handover, SH)消耗(overhead)。考慮到用戶間資料率的公平性，所提出的混合方案在細胞總生產量上也優於標準的PFR方法。因此，我們認為該方案，對於增加細胞邊緣的bit rate和整個系統的容量是一個有淺力及競爭力的方法。

第七章　總結

本計畫針對行動Wimax系統，使用一種頻域展頻的技術，將訊號在頻域作正交展頻，使用此技術的目的在於將每個載波上的資訊能量分散到所有載波上，如此一來，可以改善OFDMA在嚴重通道衰變的情況下的訊號品質。

本計畫另一核心技術在於接收端的多路徑干擾消除技術，主要目的在於對抗通道多路徑干擾的效應，利用訊號偵測與重建之間的遞迴式訊號處理，以減小訊號受到通道衰變的效應。利用多路徑干擾消除訊號處理，經過多次遞迴之後，訊號可以有越來越好的品質，經過模擬，約 3~4 次的遞迴運算即可有相當程度的改善。

本計畫另延伸Wimax-New基本系統模型,將渦輪遞迴式運算的概念加進系統裡。因為即使使用通道編碼技術，系統效能仍會受限於多路徑干擾影響，因此本計畫將渦輪等化技術與通道低密度同位檢查解碼器結合，利用解碼器所計算之後置機率，重建出每個路徑的軟式符元訊號，而每個路徑的軟式符元訊號可以回授給多路徑干擾消除模組，進行多路徑干擾消除運算，如此一來，經過幾個遞迴運算，系統便具有很好的性能。

我們可以觀察出在使用120°方向性天線，周圍有18個Co-channel cells(考慮2層的Co-channel cells)的環境下，不論是在2-path或是4-path的情形，當負載(loading)不同時，系統效能都是CDMA比OFDM來的好。雖然OFDM本身內部彼此成正交，不會互相干擾；而CDMA有MAI的問題，但是使用PEC等化器可以有效消除部分的MAI問題。尤其是當負載降低的時候，在4-path的情形，CDMA的系統效能比OFDM來得佳。

在本篇報告末了，我們提出了一個多細胞OFDMA調變在蜂巢式系統間干擾消除(inter-cell interference mitigation, ICIM)的方法，我們特別針對下行(downlink, DL)傳輸作討論。所提出方法的基本想法是於部分頻率再利用(Partial frequency reuse, PFR)和軟性換手(Soft handover, SH)間動態地作選擇，以提供蜂巢式系統中邊緣用戶較好的訊號品質。我們的模擬結果顯示，與標準的PFR相比，該方法有助於改善邊緣用戶的鏈結品質(link quality)和鏈結的頻譜效率。

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附錄

本計劃已發表兩篇論文，附錄於後。

1. C.-S. Chiu and C.-C. Huang, “Combined Partial Reuse and Soft Handover in OFDMA Downlink Transmission”, in Proc. IEEE VTC’08, May 2008, pp. 1707-1711.

2. C.-S. Chiu and C.-C. Huang, “A Hybrid Inter-Cell Interference Mitigation Scheme for an OFDMA Downlink System,” IEICE Trans. on Communication, vol.E93-B, NO.1 Jan. 2010

國科會補助專題研究計畫成果報告自評表

請就研究內容與原計畫相符程度、達成預期目標情況、研究成果之學術或應用價值（簡要敘述成果所代表之意義、價值、影響或進一步發展之可能性）、是否適合在學術期刊發表或申請專利、主要發現或其他有關價值等，作一綜合評估。

1. 請就研究內容與原計畫相符程度、達成預期目標情況作一綜合評估 ■達成目標 □ 未達成目標（請說明，以 100 字為限） □ 實驗失敗 □ 因故實驗中斷 □ 其他原因
2. 研究成果在學術期刊發表或申請專利等情形： 論文：■已發表 □未發表之文稿 □撰寫中 □無 專利：□已獲得 □申請中 ■無 技轉：□已技轉 □洽談中 ■無 其他：（以 100 字為限）
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Combined Partial Reuse and Soft Handover in OFDMA Downlink Transmission

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Abstract—**The inter-cell interference problem is a key issue in a multi-cell OFDMA system. A number of inter-cell interference mitigation schemes have been suggested to address this problem and among them, partial reuse is considered a most promising one for emerging OFDMA systems. In this paper, we propose an inter-cell interference mitigation scheme for an OFDMA downlink system. The proposed scheme makes use of a combination of partial reuse and soft handover. The basic idea of the proposed scheme is to select the better signal quality among a partial reuse scheme and a soft handover scheme for the cell edge users. Compared to the conventional partial reuse scheme, simulation results show that the cell edge throughput can be significantly improved by using the proposed scheme. Furthermore, considering the data-rate fairness among the users, the results prove that our approach can give better average cell throughput as compared with the conventional partial reuse scheme, especially for a very fair system.**

Keywords-OFDMA; interference coordination; partial reuse; soft handover

I. Introduction

To improve spectral efficiency, orthogonal frequency division multiple access (OFDMA) is considered a most promising multiple access technique in future mobile communication systems. Several communication standards, such as 3GPP LTE (Long Term Evolution), 3GPP2 UMB (Ultra Mobile Broadband), and Mobile WiMAX, all exclusively choose OFDMA as the downlink transmission scheme. With orthogonality within the cell, the main interference in an OFDMA system will be inter-cell interference. The effect of inter-cell interference is particularly detrimental to User Equipments (UEs) located at cell edge.

Important criteria for the evaluation of the systems and requirements on the performance are given in a 3GPP technical report [1]. This document lists different requirement items among which we highlight the number 3. It is: *Increase "cell edge bit rate" whilst maintaining same site locations as deployed today*. Since inter-cell interference is the main limitation factor as it causes a low cell edge bit rate, and therefore it is important to consider techniques for inter-cell interference mitigation near cell edge.

Inter-cell interference mitigation by interference coordination (IC) has been permitted in 3GPP LTE. Several schemes of interference coordination are currently being considered for 3GPP LTE, including partial reuse [2], soft reuse [3], and inverted reuse [4]. Among them, the partial reuse is seen as the most promising one in 3GPP LTE, and furthermore it has also been agreed to be a part of 3GPP2 UMB.

Looking at the radio coverage issue at cell borders in 3G CDMA systems (e.g., WCDMA, cdma2000), there is a soft handover method to address the inter-cell interference problem. Moreover, the processing gain in CDMA also helps to alleviate the cell edge interference problem. In order to go for a simplified radio access network (RAN) architecture, it is agreed that inter-Node B soft handover will not be included in 3GPP LTE, but intra-Node B soft handover (i.e., softer handover) is still a possible means [5]. Nevertheless, soft handover (i.e. MDHO) is also supported within the IEEE 802.16e-2005 standard as an optional mode.

In this paper, we introduce an inter-cell interference mitigation scheme for an OFDMA system and in particular we focus on the downlink transmission. The proposed scheme makes use of a combination of partial reuse and soft handover. The performance is evaluated under a fair share scheduler by using an OFDMA system level simulator. Simulation results show that this hybrid scheme can actually bring some throughput gains.

II. Partial Reuse and Soft Handover

In the downlink the modulated OFDMA symbols are transmitted in the unit of subchannel, and one subchannel is defined as a fixed number of OFDM subcarriers. Here, we assume that each cell always uses its maximum total transmission power, which is kept as a constant.

A. Partial Reuse (PR)

Frequency reuse factors of 1 and 3 are usually considered as the basic reuse patterns of the today OFDMA systems, because they can well suit the standard tri-sector cellular architecture. The idea of partial reuse is to partition the whole frequency band into two parts, F_1 and F_3, where F_3 further is divided into three subsets; and thus, it results in four orthogonal subbands, F_1, F_{3A}, F_{3B} and F_{3C} (see Figure 1). Note that it is reasonable to assume that F_{3A}, F_{3B} and F_{3C} have the same bandwidth. The frequency subband F_1 is called cell centre band, where a reuse factor of 1 (RF1) is adopted, and it is used by the cell interior users only. On the other hand, the frequency subband F_3 is called cell edge band, for which a reuse factor of 3 (RF3) is implemented, and the cell edge users are restricted to use this frequency subband only. However, if the cell edge band is not occupied by data of the cell edge users, it can still be used by the cell interior users.

We introduce an effective reuse factor r_{eff} which denotes the ratio of the total spectrum to the spectrum that can be used in each cell (or sector). It can be expressed by

$$r_{eff} = BW_{all} / BW_{cell} = \frac{BW_{F_1} + BW_{F_3}}{BW_{F_1} + (1/3) \cdot BW_{F_3}}, \quad (1)$$

where BW_{all} denotes the whole bandwidth; BW_{cell} denotes the available bandwidth in each cell (sector); BW_{F_1} and BW_{F_3} denote the bandwidth of reuse 1 and reuse 3, respectively.

In this study, we assume that transmitted power is equally spread over all subchannels in each cell (sector). Figure 1 shows the spectrum setting for partial reuse in a tri-sector cellular layout. As we have the constant total power assumption, the power level per subchannel can be increased in partial reuse scheme as compared with the pure reuse 1 scheme (i.e. $\alpha > \beta$ in Figure 1) and in this case, the power amplification factor α/β would be the same as the effective reuse factor.

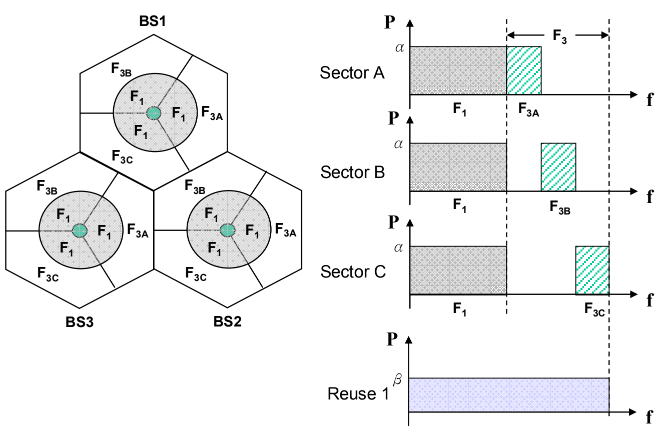

Figure 1. Spectrum setting for partial reuse in a tri-sector cell layout

B. Soft Handover

Exploiting macro-diversity through a soft handover scheme is indeed a good method to reduce the influence of inter-cell interference. When soft handover is in use, an UE is connected simultaneously to several cells, which constitute its active set. An active set is the set of cells with which an UE is communicating at any given time. The active set includes the best cell (serving cell with highest path gain) and all the cells whose path gain are greater than the difference between the highest path gain and the add threshold. Note that a soft handover scheme allows for more than one cell in the active set, while in a hard handover scheme, only one cell is ever in the active set. With downlink soft handover, the same signal is simultaneously transmitted to a single UE from multiple cells through the same subchannels. The benefit of soft handover is that the dominant interferers will become desired signals, and therefore the cell edge transmission can be remarkably improved.

The soft handover overhead [6] is an important metric, which often is used to quantify the soft handover activity in a network, and regarded as a measure of the additional required transmission resources. Note that an excessive soft handover overhead could decrease the system capacity and also bring a large number of control signaling. The soft handover overhead (η) is defined as

$$\eta = \sum_{n=1}^{N_{MAS}} n \cdot p_n - 1, \quad (2)$$

where N_{MAS} denotes the maximum active set size and p_n is the average probability of an UE being in *n*-way soft handover. In this study 1-way soft handover refers to a situation where the UE is connected to one cell, while 2-way soft handover means that the UE is connected to two cells, and so forth.

III. A Hybrid System Concept

A. Cell Interior/Edge User Partitioning

In the partial reuse scheme, one part of the spectrum has a reuse factor of 1 and for the other part of the spectrum has a reuse factor of 3. This spectrum partition works together with the split of users into cell interior users (CIUs) using the reuse 1 part and cell edge users (CEUs) using the reuse 3 part. Accordingly, in order to realize the partial reuse in an OFDMA system, we need to classify UEs into CIUs and CEUs.

A widely accepted approach is to distinguish UEs based on the geometry factor (wideband SINR measured by UE) with a predefined threshold ([7], [8]); this is because a cell edge user always causes noticeable SINR degradation. It seems a threshold of the geometry factor has to be evaluated for separating the cell interior/edge users; however any given threshold will not always fit well for different radio environments and user distributions. In this paper, we consider an UE to be a cell edge one if there are at least two cells in its handover list [6]. This means, if an UE can "see" more than one cell (i.e. this UE resides in handover region or soft handover region if soft handover is employed), then the UE will be regarded as a cell edge user. Note that every cell in the handover list is a candidate for handover and can be added to the active set. Also note that the serving cell is also a member of the handover list, thus the size of handover list is always greater than or equal to one. Since handover users will usually face a coverage problem and have a low signal quality, thus it is very reasonable to classify them as CEUs. This classification method avoids the determination of a geometry factor threshold and is based on existing handover algorithms; hence it does not require additional signaling. Therefore, we think it is very feasible for partial reuse application.

B. A Hybrid System of PR and SH for CEUs

We consider an OFDMA downlink system with partial reuse and assume that soft handover is supported. Given a cell edge UE *l*, according to the above described CIUs/CEUs classification method, we know that UE *l* resides in soft handover region (i.e. UE *l* can perform soft handover). In this case, when UE *l* is scheduled to receive data, the OFDMA system can use the following two methods to send the intended data to UE l. The first one, which is realized by soft handover, is to send data from all the cells that are in UE l's active set to UE l by using the subchannels that belong to reuse 1 subband (F_1). We name this method *Scheme A*. The second one, which is implemented by partial reuse (through a frequency reuse factor of 3), is to send data from the serving cell (sector) to UE l by using the subchannels that belong to reuse 3 subband (F_3). We denote this method as *Scheme B*.

To improve the bit rate for CEUs and also keep acceptable system capacity we develop an inter-cell interference mitigation scheme that makes use of a combination of partial reuse and soft handover. The basic idea of the proposed scheme is to select the better signal quality among a partial reuse scheme (with a reuse factor of 3) and a soft handover scheme for CEUs. In addition, for the feasibility purpose, we claim on that the soft handover overhead of the proposed scheme must be less than a typical 3G CDMA system.

Figure 2 illustrates the operational flow chat of our scheme. For a given UE k, we assume that it is served by cell-0 and we define $\gamma_{k,A}^{(1)}$ and $\gamma_{k,B}^{(3)}$ as the SINR of UE k with *Scheme A* (i.e., soft handover is applied) and *Scheme B* (i.e., a reuse 3 is applied), respectively. Herein, $\gamma^{(x)}$ denotes the SINR of a subchannel under a reuse factor x (here x=1 or 3) deployment. In the flow, firstly, cell-0 will classify UE k as a CIU or a CEU according to the size of UE k's handover list. If there is only one cell (i.e. only the serving cell) in UE k's handover list, then UE k is considered a CIU, and once UE k has the highest priority in the scheduler, cell-0 will transmit the intended data to UE k through the subchannels in the reuse 1 subband. Otherwise, UE k is considered a cell edge one and in this case, when UE k is scheduled to receive data, *Scheme A* will be adopted as a means to transmit the intended data to UE k if the condition expressed in (3) is satisfied, and *Scheme B* will be employed if the condition (3) is not hold.

$$\gamma_{k,A}^{(1)} > \gamma_{k,B}^{(3)} \tag{3}$$

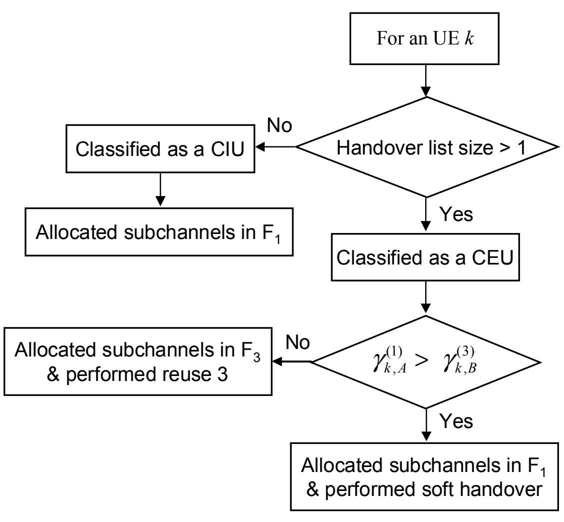

Figure 2. Flow chat of the proposed hybrid scheme

In a practical OFDMA system downlink, each UE will monitor the received pilot signal from neighboring cells over the entire available bandwidth. By measuring the long-term signal strength, each UE reports it to the serving cell. This measurement in general is used for handover purpose, but it can also be used to compute criterion (3) at the base station.

IV. System Model and Assumptions

We consider a cellular system consisting of 19 base stations (BSs), with 6 BSs in the first tier and 12 BSs in the second tier. One BS is at the center of the site, controlling the three cells (sectors), i.e., a total of 57 cells (sectors) is simulated. All the simulation results are collected from the three central cells (sectors) of the central BS. Moreover, only static coordination is considered in this paper.

A. Modeling of the downlink SINR

We assume the users are uniformly distributed within cell coverage and the serving cell is the one whose received signal is the strongest after accounting for pathloss, shadow fading, and antenna gain patterns.

In our SINR model we do not consider the fast fading; moreover, fixed and equal transmit power on each subchannel is assumed. Thus, the average SINR of each subchannel for a non-soft handover UE k, can be written as

$$\gamma_k^{(x)} = \frac{P_{sch} \cdot L_{k,s} \cdot S_{k,s} \cdot A_{k,s}}{\sum_{i \in \Phi_x} P_{sch} \cdot L_{k,i} \cdot S_{k,i} \cdot A_{k,i} + P_N}, \; (x = 1, 3) \tag{4}$$

where P_{sch} is the transmit power over a subchannel; $L_{k,j}$, $S_{k,j}$, and $A_{k,j}$ are, respectively, the pathloss, shadow fading, and antenna gain from the cell j to the UE k; the subscripts s and i stand for the serving cell and the interfering cells, respectively; Φ_1 and Φ_3 are, respectively, the set of interfering cells with a reuse factor of 1 and a reuse factor of 3 deployment with respect to UE k's position; P_N denotes the receiver noise.

Additionally, when the UE k is in soft handover, the average SINR of each subchannel for UE k can be expressed as

$$\gamma_k^{(1)} (= \gamma_{k,A}^{(1)}) = \frac{\sum_{s \in \Phi_{AS}} P_{sch} \cdot L_{k,s} \cdot S_{k,s} \cdot A_{k,s}}{\sum_{i \in (\Phi_1 - \Phi_{AS})} P_{sch} \cdot L_{k,i} \cdot S_{k,i} \cdot A_{k,i} + P_N}, \tag{5}$$

where Φ_{AS} denotes the active set of UE k and the subscripts s here stand for the cells in Φ_{AS}. Note that $\gamma_{k,A}^{(1)}$ can be calculated through (5) and further, $\gamma_{k,B}^{(3)}$ can be calculated by setting x=3 in (4).

B. Achievable Capacity Estimation

It is mentioned in [8] and [9] that the link performance from simulation is close to Shannon's equation with a loss factor, thus we adopt Shannon's equation to evaluate the performance. According to Shannon's channel capacity formula, the achievable data rate for a particular user on one subchannel is (assume a loss factor of one)

$$R = BW_{sch} \cdot \log_2(1 + SINR), \tag{6}$$

where BW_{sch} denotes the bandwidth of one subchannel.

Suppose all subchannels are fully utilized. We assume that 15 users are active for each cell, and each user has unlimited traffic to transmit on the downlink. Moreover, we also assume that the CIUs and the CEUs with *Scheme A* have equal chance of access to every subchannel on the cell centre band (F_1); and further, the CEUs with *Scheme B* have equal chance of access to every subchannel on the 1/3 cell edge band (i.e., F_{3A}, F_{3B} or F_{3C}). That is to say, a fair share scheduler in frequency domain is applied to cell centre/edge band. Note that in a fully loaded system, it becomes unlikely that CIUs would still be able to access the cell edge band, and would thus be confined to cell centre band.

If we denote the number of CIUs in a cell as K_I, and the number of CEUs in a cell as K_E, then the achievable throughput of the cell interior and cell edge can be written as (7) and (8), respectively, in which *i* stands for the CIUs and *e* stands for the CEUs.

$$T_{\text{interior}} = \sum_{i=1}^{K_I} R_i \quad (7)$$

$$T_{\text{edge}} = \sum_{e=1}^{K_E} R_e \quad (8)$$

After obtaining the achievable throughput of the cell interior and cell edge, the average cell throughput thus becomes

$$T_{\text{cell}} = T_{\text{interior}} + T_{\text{edge}} \,. \quad (9)$$

C. Frequency Partitions

We assume that the available downlink bandwidth is 5 MHz, and set the number of subchannels and the subchannel bandwidth to 25 and 180 kHz, respectively. According to the partition criterion of partial reuse and the definition of effective reuse factor in (1), we obtain the possible frequency partitions as shown in Table I. Note that allocating too many subchannels in the cell edge band is not feasible, since it will cause a large loss of available bandwidth in each cell.

D. Simulation Parameters

Static snapshot simulations have been used. An add threshold of 4 dB and a maximum active set size of 4 cells are assumed. Models and simulation parameters basically follow the 3GPP evaluation criteria case 3 [5]. A selection of simulation parameters is listed in Table II.

V. NUMERICAL RESULTS AND DISCUSSIONS

A. SINR Analysis

Given a CEU *k* that has *n* ($n \geq 2$) cells in its handover list, the probability that the received SINR of this UE with *n*-way (*n*=2, 3, 4) soft handover (i.e. *Scheme A*) will greater than that with a reuse 3 scheme (i.e. *Scheme B*) can be given as

$$\Pr(n) = P(\gamma_{k,A}^{(1)} > \gamma_{k,B}^{(3)} \,|\, N_{AS,k} = n)\,, \quad (10)$$

where $N_{AS,k}$ denotes the active set size of user *k*.

TABLE I. POSSIBLE FREQUENCY PARTITIONS

	Number of Subchannels						
Subband F_{3A} (F_{3B}, F_{3C})	1	2	3	4	5	6	7
Subband F_1	22	19	16	13	10	7	4
	Effective Reuse Factor						
γ_{eff}	1.09	1.19	1.32	1.47	1.67	1.92	2.27

TABLE II. SIMULATION PARAMETERS

Parameters	Assumptions
Cellular layout	Hexagonal grid, 19 BSs, 3 cells per BS
Carrier Frequency	2 GHz
Antenna pattern	As described in [5]
BS total Tx power	43 dBm
Site to site distance	1732 m
Distance dependent path loss	$128.1+37.6\log_{10}(R)$ (R: in km)
Minimum distance between UE and cell site	35 m
Penetration loss	20 dB
Shadowing standard deviation	8 dB
BS antenna gain	14 dBi
UE antenna gain	0 dBi
UE noise figure	9 dB
Antenna configuration	1 x 1

Simulation results of the probability as defined in (10) with different effective reuse factors are shown in Figure 3. One can see that Pr(2) is ranged between 0.1 and 0.16; Pr(3) is ranged between 0.58 and 0.69; and further, Pr(4) is about 0.97. Observe that for a cell edge UE, as the number of soft handover branches (i.e. *n*) increases, the probability that soft handover will outperform a reuse 3 scheme in SINR is increased.

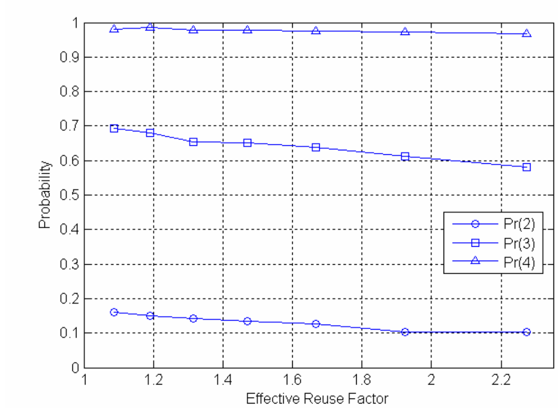

Figure 3. Probability of Pr(*n*)

B. Soft Handover Overhead Estimation

An important requirement of the proposed hybrid scheme is to have a low soft handover overhead (η) as compared with the current WCDMA systems. Table III shows the average probability of an UE being in *n*-way soft handover in the simulation system. According to (2), we know that the soft handover overhead in our method is about 0.19. It is known that in a WCDMA network, the soft handover overhead is planned to be in the order of 0.2 - 0.4 for a standard hexagonal cell grid with three sector site; and further, in a live WCDMA network in a dense urban area, the typical value of the average overhead is about 0.38 [6]. Thus we can conclude that the requirement for the overhead is comfortably met.

TABLE III. AVERAGE PROBABILITY OF AN UE BEING IN n -WAY SH

# of SH Branches	n=1	n=2	n=3	n=4
P_n	0.9	0.029	0.047	0.024

C. Achievable Throughput Evaluation

Figure 4 shows the cell interior ($T_{interior}$) and cell edge (T_{edge}) throughput for standard partial reuse scheme (PR hereafter in this section) and the proposed hybrid scheme (PR+SH hereafter in this section) with different effective reuse factors. From this figure we can have three observations. Firstly, the larger the effective reuse factor is, the smaller the total cell throughput becomes. This is due to the fact that as the effective reuse factor increases, the available bandwidth in each cell is decreased and it results in lower frequency resource utilization. Secondly, the PR+SH scheme provides a significant cell edge throughput gain (~ 20-95 %) over the PR scheme, and it gives more considerable gains when the effective reuse factor is reduced. Third, the PR+SH scheme causes about 15 % cell interior throughput loss as compared with the PR scheme. This is because in PR+SH scheme, the cell centre band (F_1) is shared between all CIUs and some CEUs (who are performing soft handover), thus the amount of frequency resources allocated to a CIU, on average, is less than that in the PR scheme. From the above observations, we know that the PR+SH scheme is a more appropriate one to achieve a uniform data rate requirement and improve cell edge bit rate.

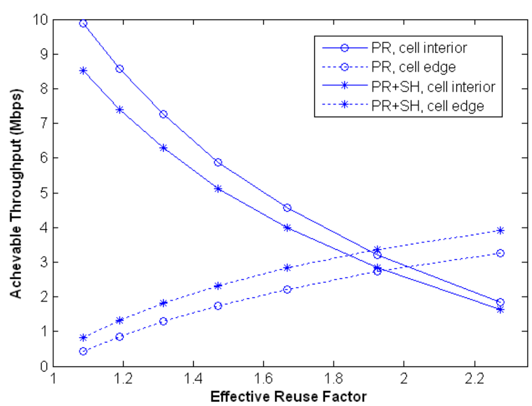

Figure 4. Average cell interior and cell edge throughput performance

Here we consider two data-rate fairness criteria, the *mean fairness* criterion and the *very fair* criterion. *Mean fairness* means that the average throughput of CEUs is approximately 3/5 of the average throughput of CIUs and *very fair* means a factor of 1 (i.e. uniform data rate). We choose the effective reuse factors, which can nearly fulfill the predefined fairness criteria, from Table I. According to our simulation results, the selected factors that can closely achieve *mean fairness* are 1.47 and 1.32 for the PR and the PR+SH schemes, respectively; and for a *very fair* system, these values are 1.67 and 1.47 for the PR and the PR+SH schemes, respectively.

The average cell throughput performance under *mean fairness* and *very fair* criteria is reported in Figure 5. For comparison, the reuse 1 and 3 results are also illustrated in the figure. The results show that compared to the PR scheme, the PR+SH scheme can achieve about 6 % and 10% average cell throughput gains in the *mean fairness* and *very fair* systems, respectively. It can be explained as follows. Due to the consideration of the data-rate fairness among the users, the PR+SH scheme can distribute the user throughput more fairly to the users than the standard PR scheme. For a given data-rate fairness criterion, the proposed scheme can meet the criterion with smaller effective reuse factor as compared with the PR scheme. We notice that the reuse factor 1 deployment maximizes the cell throughput but suffers from the fairness problem, and the reuse 3 deployment has the lowest capacity.

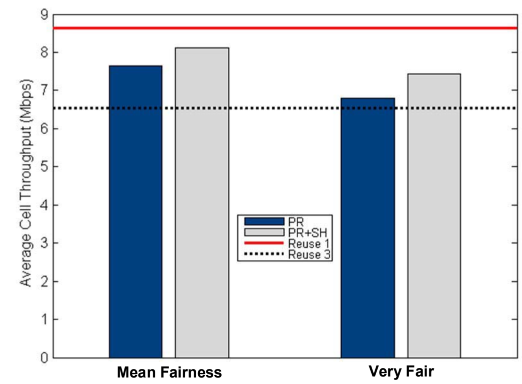

Figure 5. Average cell throughput performance

VI. CONCLUSIONS

In this paper, we propose an inter-cell interference mitigation scheme that makes use of a combination of partial reuse and soft handover for an OFDMA downlink system. The simulated results show that our approach gives a significant cell edge throughput gain over the conventional partial reuse scheme, and it also has the advantage of having a low soft handover overhead. Besides, under the defined data-rate fairness criteria, our results prove that the proposed hybrid scheme outperforms the partial reuse scheme in total cell throughput, especially for a very fair system. So we conclude that the proposed scheme is a competitive choice to enhance the cell edge bit rate and also overall system capacity.

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PAPER

A Hybrid Inter-Cell Interference Mitigation Scheme for an OFDMA Downlink System*

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Summary
A number of inter-cell interference coordination schemes have been proposed to mitigate the inter-cell interference problem for orthogonal frequency division multiple access (OFDMA) systems and among them, partial frequency reuse is considered one of the most promising approaches. In this paper, we propose an inter-cell interference mitigation scheme for an OFDMA downlink system, which makes use of both partial frequency reuse and soft handover. The basic idea of this hybrid scheme is to dynamically select between a partial frequency reuse scheme and a soft handover scheme to provide better signal quality for cell edge users. Compared with the standard partial frequency reuse scheme, simulation results show that approximately one quarter of cell edge users can get improvements in signal quality as well as link spectral efficiency from using the proposed hybrid scheme. We also observe that by using our approach, there is a significant cell edge throughput gain over the standard partial frequency reuse scheme. Furthermore, based on a well defined data rate fairness criterion, we show that our method achieves higher overall system capacity as compared with the standard partial frequency reuse scheme.

Key words:
OFDMA, inter-cell interference, interference coordination, partial frequency reuse, soft handover.

1. Introduction

Orthogonal frequency division multiplexing (OFDM) is a transmission technique that has been widely accepted as a suitable solution for broadband wireless communications. As an extension, OFDM could be used not only as a modulation scheme, but also as part of the multiple access technique as well, namely orthogonal frequency division multiple access (OFDMA). Recently, OFDMA is considered a most promising multiple access technique to improve spectral efficiency in future mobile communication systems. Several communication standards, such as 3rd Generation Partnership Project (3GPP) LTE (Long Term Evolution), 3rd Generation Partnership Project 2 (3GPP2) UMB (Ultra Mobile Broadband), and Mobile WiMAX (Worldwide Interoperability for Microwave Access), all exclusively choose OFDMA as the downlink transmission scheme [1][2][3]. With orthogonality within the cell, the main interference in an OFDMA system comes from inter-cell interference. The inter-cell interference is particularly disadvantageous to user equipments (UEs) located at cell edge, especially for a multi-cell OFDMA system with universal frequency reuse.

Important criteria for system evaluation and performance requirements are given in a 3GPP technical report [4]. This document lists different requirement items among which we highlight the particular one which says, “Increase cell edge bit rate whilst maintaining same site locations as deployed today”. This criterion indicates that the cell edge quality of service (QoS) is an important performance requirement. For delivering a uniform user throughput across the whole cell area, inter-cell interference is the main limitation factor as it causes a low cell edge bit rate. Therefore, it is important to consider techniques to mitigate inter-cell interference for cell edge users.

To deal with this interference problem, several pre-4th generation (pre-4G) systems, like 3GPP LTE, 3GPP2 UMB, and Mobile WiMAX, employ inter-cell interference coordination as an interference mitigation scheme. The common theme of inter-cell interference coordination is to apply restrictions to the usage of downlink/uplink resources e.g., time/frequency resources and/or transmit power resources. Such coordination will provide a way to avoid severe inter-cell interference, and thus provide more balanced bit rates among UEs. Several inter-cell interference coordination schemes have been proposed for OFDMA systems, including partial frequency reuse [5][6], soft frequency reuse [7][8], inverted frequency reuse [9], etc.. Among them, partial frequency reuse (also known as fractional frequency reuse), one of the most promising approaches, is considered in 3GPP LTE, and it is supported in Mobile WiMAX and 3GPP2 UMB.

To improve radio coverage at cell borders in 3rd generation (3G) code division multiple access (CDMA) systems (e.g., WCDMA, cdma2000), soft handover which exploits macro diversity has already been used to address the inter-cell interference problem. Moreover, the processing gain in CDMA also helps to alleviate the cell edge interference problem. In order to maintain a simplified radio access network (RAN) architecture, it is agreed that soft handover will not be included in 3GPP LTE. Nevertheless, soft handover is supported in the IEEE 802.16e-2005 standard as an option (known as macro diversity handover in IEEE 802.16e-2005) [3].

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*This paper is the revised and extended version of a paper presented at IEEE VTC2008-Spring, May 2008 [24].

Conventionally, frequency reuse scheme is used in OFDMA, and soft handover scheme (exploiting macro diversity) in CDMA. In this paper, we introduce a hybrid inter-cell interference mitigation scheme for an OFDMA system, and in particular we concentrate on the downlink transmission. The proposed scheme makes use of both partial frequency reuse and soft handover. The motivation for developing this hybrid method is that, for a cell edge user, it is possible that a soft handover scheme may provide higher signal quality than a partial frequency reuse scheme and thus, it gives the possibility of improving cell edge bit rate. Simulation results show that this hybrid scheme can actually bring some capacity gains for the whole system as well as improve signal quality for cell edge users.

The rest of this paper is organized as follows. In Section II, we describe the partial frequency reuse scheme. In Section III, we illustrate the soft handover scheme. In Section IV, we explain the proposed hybrid system concept. In Section V, we present the system model, measures and assumptions for the performance evaluation. Our simulation results and discussions are given in Section VI. Finally, we give conclusions in Section VII.

2. Partial Frequency Reuse Description

In order to maximize spectral efficiency, the emerging OFDMA systems like 3GPP LTE, 3GPP2 UMB and Mobile WiMAX all assume that a frequency reuse factor of 1 should be used, i.e., the same frequency band can be used in any cell (sector) of the system[†]. Although full frequency reuse may ensure the best throughput, it brings low signal quality for cell edge users due to inter-cell interference. A more realistic frequency reuse scheme which adopts a frequency reuse factor of 3 in a tri-sector network significantly reduces inter-cell interference but induces a reduction to the accessible frequency resources in each cell. In a tri-sector network, a frequency reuse factor of 3 means that a frequency subchannel can only be reused in one of the three sectors of the same site. Frequency reuse factors of 1 and 3 are usually used to generate frequency reuse patterns of the nowadays OFDMA systems, as they well suit the conventional tri-sector cellular architecture. For CDMA systems, a frequency reuse factor of 1 is normally used because CDMA takes advantage of processing gain achieved through using nearly orthogonal spreading codes.

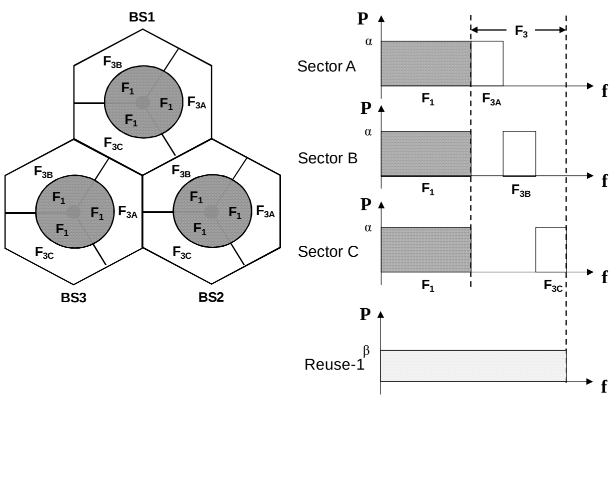
Partial frequency reuse or simply partial reuse (PR) is an inter-cell coordination scheme that applies restrictions to the frequency resources in a coordinated way among cells. The idea of partial frequency reuse is to partition the whole frequency band into two parts, F_1 and F_3, where F_3 is further divided into three subsets; and thus, it results in four orthogonal subbands, F_1, F_{3A}, F_{3B} and F_{3C} (see Fig. 1). Note that it is reasonable to assume that F_{3A}, F_{3B} and F_{3C} have the same bandwidth. The frequency subband F_1 is called the cell center band, for which a frequency reuse factor of 1 (reuse-1) is adopted, and it is used by the cell interior users only. On the other hand, the frequency subband F_3 is called the cell edge band, for which a frequency reuse factor of 3 (reuse-3) is implemented, and the cell edge users are restricted to use this frequency subband only. Nevertheless, when the cell edge band is not occupied by the cell edge users, it can also be used by the cell interior users.

In [11], an effective reuse factor (ERF) r_{eff} is introduced to represent the ratio of the total spectrum to the spectrum that can be used in each cell, and it can be expressed by

$$r_{eff} = BW_{all} / BW_{cell} = \frac{BW_{F_1} + BW_{F_3}}{BW_{F_1} + (1/3) \cdot BW_{F_3}}, \qquad (1)$$

where BW_{all} denotes the whole bandwidth; BW_{cell} denotes the available bandwidth in each cell; BW_{F_1} and BW_{F_3} denote the bandwidth of reuse-1 and reuse-3 subbands, respectively. Note that the whole bandwidth is the sum of bandwidth BW_{F_1} and BW_{F_3}, and each cell can use the entire BW_{F_1} and 1/3 of BW_{F_3}, i.e., $BW_{F_{3A}}$, $BW_{F_{3B}}$ or $BW_{F_{3C}}$.

In this study, we assume that each cell always uses its maximum transmission power, which is kept as a constant, and we also assume that transmit power is equally spread over the whole available bandwidth in each cell (i.e. a flat transmission power spectrum density is assumed). Figure 1 shows the spectrum setting for partial frequency reuse in a tri-sector cellular layout. As we have the constant total power assumption, the transmit power level α can be increased in partial frequency reuse scheme as compared with the pure reuse-1 scheme (i.e. $\alpha > \beta$ in Fig. 1) and in this case, the power amplification factor α / β would be the same as the effective reuse factor.



[†]Normally, the geographical areas that are controlled by the same base station (or Node B) are known as sectors. However, the terms cell and sector are interchangeable in this paper.

Fig. 1 Spectrum setting for partial frequency reuse in a tri-sector cellular layout

3. Soft Handover Description

One of the main macro diversity methods in 3G CDMA downlink is soft handover (SH). Exploiting macro-diversity with a soft handover scheme is indeed a good method to reduce the influence of inter-cell interference. When soft handover is in use, an UE is connected simultaneously to several cells, which constitute its active set. An active set is the set of cells with which an UE is communicating at a given time. The active set includes the best cell (serving cell with highest path gain) and all the cells whose path gain are larger than the highest path gain minus the add threshold (Window_add [12]). Note that a soft handover scheme allows for more than one cell in the active set, while in a hard handover scheme, there is only one cell in the active set. With soft handover, the same signal is simultaneously transmitted to an UE from multiple cells through the same frequency subchannels. The benefit of soft handover comes from the fact that the dominant interferers become desired signals, and therefore, the cell edge transmission quality can be remarkably improved.

The soft handover overhead [12] is an important metric used to quantify the soft handover activity in a network, and it is regarded as a measure of additional transmission resources required. Note that a large soft handover overhead also implies a large number of control signaling and it decreases the system capacity. The soft handover overhead (η) is defined as

$$\eta = \sum_{n=1}^{N_{MAS}} n \cdot P_n - 1, \qquad (2)$$

where N_{MAS} denotes the maximum active set size and P_n is the probability of an UE being in *n*-way soft handover. In this study, 1-way soft handover indicates the case that an UE is connected to only one cell, while 2-way soft handover indicates that the UE is connected to two cells, and so forth.

4. A Hybrid System Concept

4.1 Cell Interior/Edge Users Partition

In the partial frequency reuse scheme, one part of the spectrum has a frequency reuse factor of 1 and the other part has a frequency reuse factor of 3. This spectrum partition works together with the split of users into cell interior users (CIUs) using the reuse-1 part of spectrum and cell edge users (CEUs) using the reuse-3 part of spectrum. Accordingly, for realizing the partial frequency reuse in an OFDMA system, we need to classify UEs into CIUs and CEUs.

A widely accepted approach to partition UEs is based on the geometry factor (G-factor). The G-factor is the wideband average SINR (signal to interference plus noise power ratio) measured by an UE from pilot subcarriers over the reuse-1 part of the spectrum (F_1). The G-factor is then compared with a predefined threshold to determine whether the UE is a cell interior user or a cell edge user [8][13][14][15]. This is because a cell edge user always suffers from noticeable SINR degradation. The average SINR of an UE is defined as the ratio of totally received wideband own-cell power and other-cell interference plus noise power at the UE. It should be noted that the SINR is averaged over short-term fading, but not shadowing. In this paper, we consider an UE as a cell edge user which has to be protected by an inter-cell interference mitigation scheme, e.g., by a reuse-3 scheme or a soft handover scheme, if the G-factor measured at the UE is smaller than a threshold of 0 dB [13][15][16]; otherwise, the UE is regarded as a cell interior user.

4.2 Problem Formulation

We consider an OFDMA downlink system with partial frequency reuse; and further, we assume that soft handover (including softer handover) is supported. Assume that an UE is a cell edge user and there is more than one cell in the UE's handover list. The handover list is the list of cells whose link quality satisfies the soft handover requirement, and thus every cell in the list can be added to active set. Note that the serving cell is certainly a member of the handover list, thus the size of handover list is always greater than or equal to one. In this situation, the OFDMA downlink system can use either of the following two methods to send the intended data to the UE. The first method is based on soft handover and the OFDMA downlink system sends data from all the cells that are in the UE's active set to the UE by using the frequency subchannels that belong to reuse-1 subband F_1. We name this method *Scheme A*. The second method is based on partial frequency reuse (through a frequency reuse factor of 3) and the OFDMA downlink system sends data from the serving cell to the UE by using the frequency subchannels that belong to reuse-3 subband of the cell, i.e. F_{3A}, F_{3B}, or F_{3C}. We denote this method as *Scheme B*. Note that in *Scheme A*, the active set is exactly the set of cells in the handover list, and in *Scheme B*, the active set corresponds to only the serving cell.

In the above scenario, two remaining questions are: 1) Which scheme (*Scheme A* or *Scheme B*) could provide higher signal quality (SINR) for the UE? 2) As compared with the standard partial frequency reuse scheme (i.e. without soft handover option), can we generate some throughput gains by dynamically choosing between *Scheme A* and *Scheme B*? These two questions are addressed in the following sections.

4.3 A Hybrid System of PR and SH

To enhance cell edge bit rate and overall system capacity, we develop an inter-cell interference mitigation scheme that dynamically chooses between *Scheme A* and *Scheme B* according to which scheme provides better signal quality (SINR). For the standard partial frequency reuse scheme, a serving cell will first classify an UE as a CIU or a CEU according to the UE's G-factor. If the G-factor is greater than a predefined threshold (e.g., 0 dB in this paper), the UE is considered as a cell interior user and the serving cell will transmit the intended data to the UE through the frequency subchannels in the reuse-1 subband; otherwise, the UE is treated as a cell edge user and the serving cell will use the frequency subchannels with a reuse factor of 3 (i.e. *Scheme B*) to send the intended data to the UE.

Figure 2 shows the operational flow chart of the proposed hybrid scheme. For the proposed scheme, a cell edge user may be allocated either frequency subchannels with a reuse factor of 3 or frequency subchannels with a reuse factor of 1 and use soft handover. We note that the operations of CIUs are the same for the standard partial frequency reuse and the proposed hybrid schemes. With Fig. 2, when an UE is classified as a cell edge user, the serving cell will use *Scheme B* to transmit the intended data to the UE if there is only one cell in the UE's handover list. On the other hand, if the UE's handover list size is larger than one, then the serving cell will dynamically select either *Scheme A* or *Scheme B* to transmit the intended data to the UE and the selection criterion is based on signal quality comparison, which can be expressed as

$$\text{If } \gamma_A^{(1)} > \gamma_B^{(3)}, \text{ choose Scheme A; otherwise, choose Scheme B.} \quad (3)$$

where $\gamma_A^{(1)}$ and $\gamma_B^{(3)}$ are the SINR measured by the UE with *Scheme A* (soft handover applied) and *Scheme B* (partial frequency reuse applied), respectively. Here, the superscript x (x=1 or 3) of $\gamma^{(x)}$ indicates that the SINR is measured on the reuse-x subband.

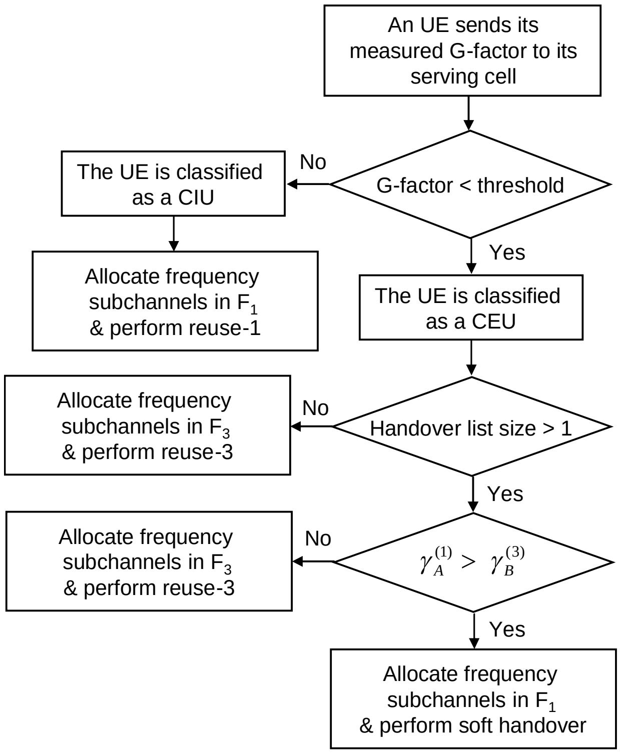


Fig. 2 Operational flow chart of the proposed hybrid scheme

5. System Model, Measures and Assumptions

Partial frequency reuse can be achieved by either static coordination or dynamic coordination. Since dynamic coordination introduces large signaling overhead and scheduling complexity, a static coordination is highly recommended [17][18]. In this paper, only static coordination is considered.

5.1 Modeling of Downlink Average SINR

In our SINR calculation, we do not consider fast fading and assume radio link is subject to propagation loss and log-normally distributed shadowing. We further assume that the serving cell is the one from which the received signal is the strongest after accounting for pathloss, shadow fading, and antenna gain patterns.

Suppose all frequency subchannels designated for each cell are fully utilized (i.e. a fully loaded system) and we have the equal power allocation assumption, the transmission power spectrum density P_t (or transmit power level α, see Fig. 1) is given by

$$P_t = P_T / BW_{all} \cdot r_{eff} (= P_T / BW_{cell}) , \quad (4)$$

where P_T denotes total transmission power. Thus, the average SINR for an (non-soft handover) UE can be written as

$$\gamma^{(x)} = \frac{P_t \cdot L_s \cdot S_s \cdot A_s}{\sum_{i \in \Phi_x} P_t \cdot L_i \cdot S_i \cdot A_i + P_N}, \ (x = 1,3) \quad (5)$$

where L_j, S_j, and A_j are the pathloss, shadow fading and antenna gain from the cell j to the UE, respectively; the subscripts s and i stand for the serving cell and the interfering cells, respectively; Φ_1 and Φ_3 are the sets of interfering cells with a reuse factor of 1 and a reuse factor of 3, respectively; P_N denotes the received noise power spectrum density.

Moreover, when the UE is in soft handover, its average SINR can be expressed as

$$\gamma_A^{(1)} = \frac{\sum_{s \in \Phi_{AS}} P_t \cdot L_s \cdot S_s \cdot A_s}{\sum_{i \in (\Phi_1 - \Phi_{AS})} P_t \cdot L_i \cdot S_i \cdot A_i + P_N}, \quad (6)$$

where Φ_{AS} denotes the active set of the UE and the subscript s stands for the cells in the active set. In order to evaluate condition (3), we note that $\gamma_A^{(1)}$ can be calculated directly from (6) and $\gamma_B^{(3)}$ can be calculated by setting x=3 in (5).

5.2 Link Spectral Efficiency Evaluation

According to Shannon's capacity formula [19], the achievable link spectral efficiency C (bps/Hz) from a BS to a particular user is a function of the average received SNR (signal to noise ratio). In general, Shannon's formula gives the capacity of an additive white Gaussian noise (AWGN) channel and it is not applicable to a multipath channel. Assume that other-cell interference can be modeled as AWGN and we do not consider other-cell interference cancellation techniques in the receiver, a modified Shannon formula has been introduced in [20] to calculate link capacity in a cellular mobile radio communication system. This formula is given as

$$\tilde{C}(\gamma) = \xi \cdot \log_2(1 + \gamma / \varsigma) \ bps / Hz. \quad (7)$$

where ξ and ς are constants that account for the system bandwidth efficiency and the SINR implementation efficiency, respectively, and γ denotes the average received SINR. For Typical Urban (TU) channel model and Single-Input Single-Output (SISO) antenna scheme, it has been shown in [20] that Equation (7) with $\xi = 0.56$ and $\varsigma = 2$ achieves a good match to the link capacity performance of 3GPP LTE from simulation. Therefore, we adopt this modified Shannon capacity equation with parameters $\xi = 0.56$ and $\varsigma = 2$ to evaluate the link spectral efficiency.

5.3 System Capacity Estimation

We assume that the users are uniformly distributed within cell coverage, and each user has unlimited traffic to transmit on the downlink. Moreover, it is assumed that a Round Robin (RR) scheduler is applied to cell center/edge bands. Under the RR scheduling policy, the system capacity T can be calculated as [20][21]

$$T = BW \cdot \nu \cdot \int \tilde{C}(\gamma) f_\gamma(\gamma) d\gamma, \quad (8)$$

where ν is a loss factor that accounts for the system overhead, $f_\gamma(\gamma)$ is the probability density function of SINR γ, and BW denotes the allocated bandwidth. In this paper, the loss factor ν is set to 1; this yields optimistic results, but is deemed acceptable for relative comparison purposes.

In a fully loaded system, it becomes unlikely that CIUs would be able to access the cell edge band (i.e. F_3), and they would thus be confined to cell center band (i.e. F_1). This causes a separation of user groups such that the CIUs occupy the cell center band only while the CEUs use the cell edge band only. From (8), the average cell interior throughput ($T_{Interior}$) and cell edge throughput (T_{Edge}) for the partial frequency reuse scheme can be calculated by (9) and (10), respectively,

$$T_{Interior} = BW_{F_1} \cdot \int \tilde{C}(\gamma_I) f_{\gamma_I}(\gamma_I) d\gamma_I, \quad (9)$$

$$T_{Edge} = \frac{1}{3} BW_{F_3} \cdot \int \tilde{C}(\gamma_E) f_{\gamma_E}(\gamma_E) d\gamma_E, \quad (10)$$

in which the subscripts I and E stand for the CIUs and CEUs, respectively.

With the proposed hybrid scheme, as we have a RR scheduling policy on the cell center band, two user groups, the CIUs and the CEUs with *Scheme A*, will have equal chance of access to the frequency subchannels on the cell center band. Accordingly, the average cell interior throughput and cell edge throughput can be calculated by (11) and (12), respectively,

$$T_{Interior} = BW_{F_1} \cdot \frac{P_I}{P_I + P_2 + P_3} \cdot \int \tilde{C}(\gamma_I) f_{\gamma_I}(\gamma_I) d\gamma_I, \quad (11)$$

$$T_{Edge} = \frac{1}{3} BW_{F_3} \cdot \int \tilde{C}(\gamma_{E,B}) f_{\gamma_{E,B}}(\gamma_{E,B}) d\gamma_{E,B} + \sum_{n=2}^{3} \left(\frac{1}{n} \cdot BW_{F_1} \cdot \frac{P_n}{P_I + P_2 + P_3} \cdot \int \tilde{C}(\gamma_{E,A,n}) f_{\gamma_{E,A,n}}(\gamma_{E,A,n}) d\gamma_{E,A,n}\right), \quad (12)$$

in which P_I denotes the (statistically) probability of CIUs (ratio of CIUs to total users in number); P_n denotes the (statistically) probability of an UE being in n-way soft handover (that is the ratio of users with n-way soft handover to total users in number); and subscripts A and B represent *Scheme A* and *Scheme B* users, respectively.

Note that in (15), $1/n$ that appears on the right hand side represents the capacity loss factor that is induced by performing a *n*-way soft handover. In this paper, a maximum active set size of 3 cells ($N_{MAS} = 3$) [22] and an add threshold of 4 dB (Window_add = 4 dB) [22] are assumed.

After obtaining the average throughput of the cell interior users and cell edge users, the average (total) cell throughput (T_{Cell}) thus becomes

$$T_{Cell} = T_{Interior} + T_{Edge} \,. \tag{13}$$

5.4 Simulation Method and Simulation Parameters

Static snapshot simulations have been used. The average SINR distribution (i.e. $f_\gamma(\gamma)$) is obtained through Monte Carlo simulations involving 2000 random placement of users geographically. Simulation assumptions and parameters basically follow the 3GPP evaluation criteria [10]. The available downlink bandwidth is fixed at 10 MHz. We consider a multi-cell system consisting of 19 base stations (BSs). A BS controls the three sectors (cells), i.e., 57 sectors (cells) in total are considered. The radio links are subject to distance-dependent propagation loss and lognormal shadowing fading. A distance-dependent path loss with a propagation loss exponent of 3.76 and a lognormal shadowing with a standard deviation of 8 dB are assumed. The sector antenna pattern used in our simulation is adopted from [10]. All the simulation results are collected from the three sectors of the central BS and the remaining 54 sectors act as a source of inter-cell interference. Table 1 summarizes the main simulation parameters.

Table 1: Simulation parameters

Parameters	Assumptions
Cellular layout	Hexagonal grid, 19 BSs, 3 cells per BS
Carrier Frequency	2 GHz
System bandwidth	10 MHz
Antenna pattern	As described in [10]
BS total Tx power	46 dBm
Site to site distance	1732 m
Distance dependent path loss	$128.1+37.6\log_{10}(R)$ (R: in km)
Minimum distance between UE and cell site	35 m
Penetration loss	20 dB
Shadowing standard deviation	8 dB
Shadowing correlation between BSs / sectors	0.5 / 1
BS antenna gain	14 dBi
UE antenna gain	0 dBi
UE noise figure	9 dB
Antenna configuration	1 x 1

6. Numerical Results and Discussions

The simulation results are conducted for the standard partial frequency reuse (PR hereafter in this chapter) and the proposed hybrid scheme (PR+SH hereafter in this chapter). Furthermore, we consider the effective reuse factor (ERF) r_{eff} ranged between 1.1 and 2. Note that allocating a large number of frequency subchannels in the cell edge band will also cause a large loss in bandwidth utilization in each cell. Thus, we limit the effective reuse factor to 2, which in turn about 3/4 frequency resources are reserved for cell edge band F_3.

To begin with, it is beneficial to know the percentages of CIUs and CEUs in the simulation system. The cumulative distributed functions (CDFs) of downlink G-factor over the whole cell area are plotted in Fig. 3 for r_{eff} =1.2, 1.5, and 1.8. With a classification threshold of 0 dB, one can see that the percentage of CEUs within a cell is about 34% ($P_E \approx 0.34$) and that value for CIUs is about 66% ($P_I \approx 0.66$). Furthermore, since we assume that site-to-site distance is equal to 1732 m (see Table 1), the evaluation system will be interference limited, and thus one can find that the CDF is almost not changed by different effective reuse factors.

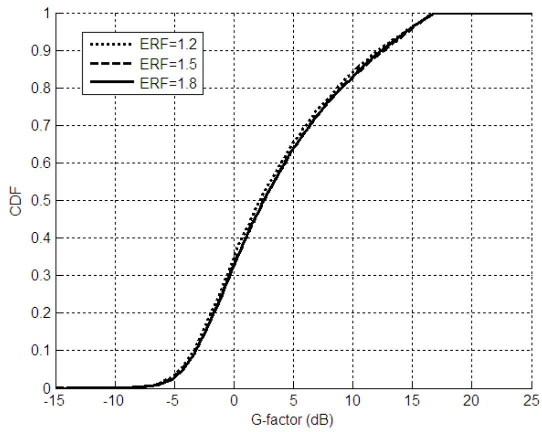


Fig. 3 G-factor distributions over cell area

6.1 Soft Handover Overhead Estimation

Here, we study the soft handover overhead (η) of the proposed hybrid scheme. For feasibility reason, an important requirement of the PR+SH scheme is to have a low soft handover overhead as compared with the current 3G CDMA systems. Table 2 shows the probability of an UE being in *n*-way soft handover (P_n) for the simulated system. Applying the simulation results to (2), we found that the induced soft handover overhead of the PR+SH scheme is about 0.15. It is known that in a WCDMA network, the soft handover overhead is around 0.2-0.4 for a standard hexagonal cell grid with three sector sites [12]; and furthermore, in a live WCDMA network in a dense urban area, the typical value of the average overhead is about 0.38 [12]. Thus we conclude that the soft handover overhead of the simulated PR+SH scheme is relatively small.

Table 2: Probability of An UE Being in *n*-way SH

# of SH Branches	n =1	n=2	n=3
P_n	~0.91	~0.03	~0.06

6.2 Average SINR Comparison

Given a cell edge UE with $n \geq 2$ cells in its handover list, the probability that the received SINR of the UE with *n*-way (*n*=2, 3) soft handover (i.e. *Scheme A*) will be larger than that with a reuse-3 scheme (i.e. *Scheme B*) can be written as

$$P(n) = P(\gamma_A^{(1)} > \gamma_B^{(3)} \,|\, N_{AS} = n), \tag{14}$$

where N_{AS} denotes the active set size of the UE.

Our simulation results of the probability as defined in (14) with different effective reuse factors are shown in Fig. 4. It can be observed that *P*(2) is ranged between 0.14 and 0.20 and *P*(3) is ranged between 0.62 and 0.70. Hence, we conclude that as the number of soft handover cells (i.e. *n*) increases, the probability that the soft handover scheme will outperform a reuse-3 scheme in average SINR will also be increased.

The average SINR distributions of CEUs with handover list size greater than one are shown in Fig. 5 for r_{eff} =1.2, 1.5, and 1.8. It is observed that by using the PR+SH scheme, the average SINR of the CEUs with handover list size greater than one is increased by approximately 1.8 dB, on average, when comparing with the standard PR scheme. To link up the results with Table 2, we conclude that about 9% (P_2+P_3) of total users or 26% ((P_2+P_3)/P_E) of CEUs will get SINR improvement by using the PR+SH scheme, and the relative gain is about 1.8 dB, on average.

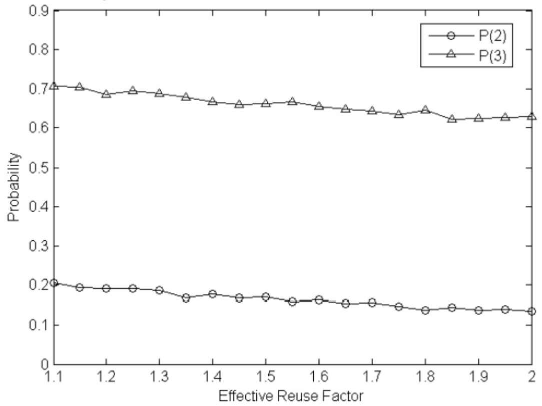


Fig. 4 Simulation results of *P*(*n*)

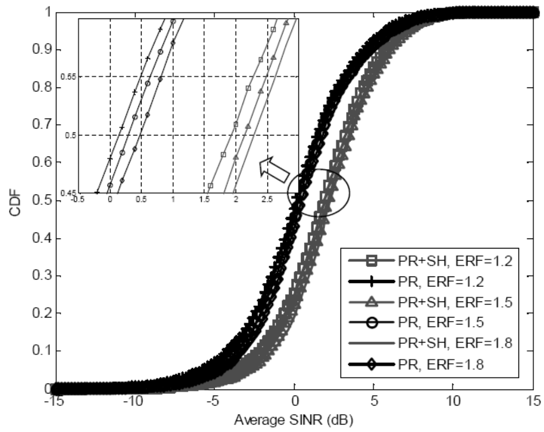


Fig. 5 Average SINR distributions of CEUs with handover list size > 1

6.3 Link Spectral Efficiency Comparison

A more meaningful metric to look at is the improvement in link spectral efficiency (SE) by accounting for the bandwidth loss effect from the soft handover scheme and the reuse-3 scheme. The condition for this link spectral efficiency improvement can be expressed as

$$\frac{1}{n} \cdot \log_2(1+\gamma_A^{(1)}/\varsigma) > \frac{1}{3} \cdot \log_2(1+\gamma_B^{(3)}/\varsigma), \tag{15}$$

where *n* denotes the number of soft handover cells. It is noted that for a cell edge UE with 2-way or 3-way soft handover, the event $\gamma_A^{(1)} > \gamma_B^{(3)}$ does imply that inequality (15) holds and thus leads to link capacity improvement. To capture the link capacity improvement, we further define the *effective link SE* $\tilde{C}_{eff}$ as

$$\tilde{C}_{eff}(\gamma) = \frac{1}{m} \tilde{C}(\gamma), \tag{16}$$

where *m* is a bandwidth loss factor accounting for a reuse-3 scheme (*m*=3) or a soft handover scheme (*m*=2 or 3). We note that the loss factor *m* is set to 1 for the CIUs.

For 3GPP LTE, the link SE at 5 % point of its CDF (i.e. 95% coverage), called 5% user SE, is an important criterion for performance evaluation of different inter-cell interference mitigation schemes [10][21][23]. Therefore, we adopt this criterion as a performance comparison indicator here. Figure 6 demonstrates the effective link SE $\tilde{C}_{eff}$ distributions with r_{eff} =1.2, 1.5, and 1.8; and in particular we focus on the low user SE region. From the figure we observe that the 5% user SE of the PR+SH scheme is about 1.3 times of that of the standard PR scheme.

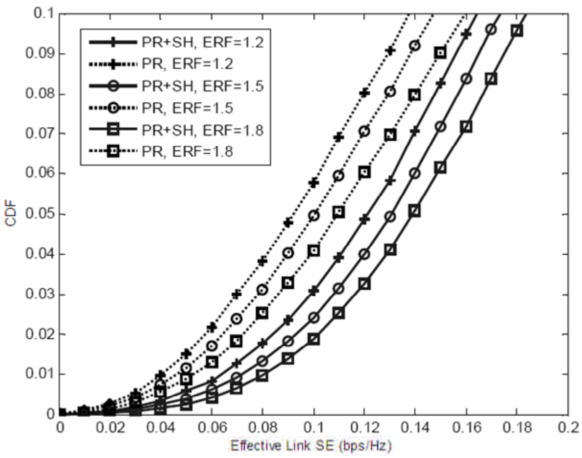


Fig. 6 Effective Link SE $\tilde{C}_{eff}$ distribution

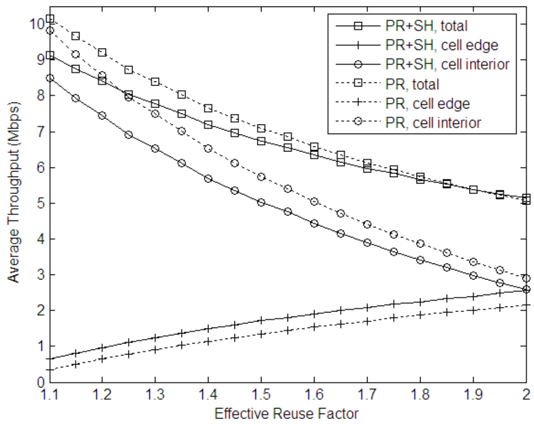


Fig. 7 Average throughput performance

6.4 System Capacity Comparison

Figure 7 shows the average (total) cell throughput (T_{Cell}), cell interior throughput ($T_{Interior}$) and cell edge throughput (T_{Edge}) for the standard PR scheme and the PR+SH scheme with different effective reuse factors. From this figure we can have three observations. First, the larger the effective reuse factor is, the smaller the total cell throughput becomes. This is due to the fact that as the effective reuse factor increases, the available bandwidth in each cell is decreased and it results in lower frequency resource utilization. Second, the PR+SH scheme provides a significant cell edge throughput gain (about 18-92 %) over the PR scheme, and the gain is more significant when the effective reuse factor is reduced. Third, with the same effective reuse factor, the PR+SH scheme causes about 11-13 % cell interior throughput loss as compared with the PR scheme, and this further results in total cell throughput degradation when the effective reuse factor is less than 1.85 (roughly). This is because in the PR+SH scheme, the cell center band (F_1) is shared between all CIUs and some CEUs (who are performing soft handover), thus the amount of frequency resource allocated to a CIU, on average, is less than that in the PR scheme. From the above observations, one can conclude that the PR+SH scheme is an appropriate method to improve cell edge bit rate and achieve data rate fairness among users.

In a wireless communication system, it is very important to consider data rate fairness among users. Here, we define a parameter *f*, called *data rate fairness index*, as

$$\frac{T_{Interior}}{N_u \cdot P_I} = f \cdot \frac{T_{Edge}}{N_u \cdot P_E}, \qquad (17)$$

where N_u denotes the number of active users in one cell and P_E is the (statistically) probability of CEUs (ratio of CEUs to total users in number). In this study, we consider three data rate fairness cases [11]: the first one is *f*=1, which is called *fair*; the second case is *f*=2, which is called *less fair*; and the last one is *f*=3, which is called *least fair*. In the above three cases, the average user throughputs of CEUs are approximately 100%, 50%, and 33.3% of the average user throughputs of CIUs, respectively.

Our simulation results of the average cell throughput at different data rate fairness index *f* are presented in Fig. 8. For comparison, we also show the pure reuse-1 deployment result in the figure. Note that in reuse-1 deployment case the value of *f* is fixed and is approximately 5.1 from our simulation. As shown in Fig. 8, both PR and PR+SH schemes outperform reuse-1 assuming *f*=5.1. This result implies that the influence of accessible bandwidth loss caused by using PR or PR+SH scheme can be regained, and it further leads to an improvement in throughput. From Fig. 8 one can observe that, as compared with the standard PR scheme, the PR+SH scheme can achieve about 8%, 5%, and 3% average cell throughput gains in the *fair*, *less fair*, and *least fair* cases, respectively. The performance improvement can be explained as follows: due to the consideration of the data rate fairness among users, the PR+SH scheme can distribute the user throughput more evenly to the users than the standard PR scheme. In other words, the PR+SH scheme can meet a given data rate fairness index by using a smaller effective reuse factor as compared with the standard PR scheme. Figure 9 shows data rate fairness index *f* as a function of the effective reuse factors. Take the *f*=1 case as an example, the corresponding effective reuse factors are 1.83 and 1.68 for the PR scheme and the PR+SH scheme, respectively.

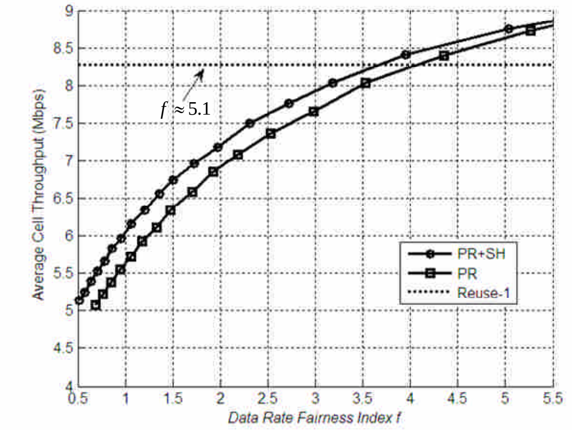


Fig. 8 Average cell throughput performance vs. data rate fairness

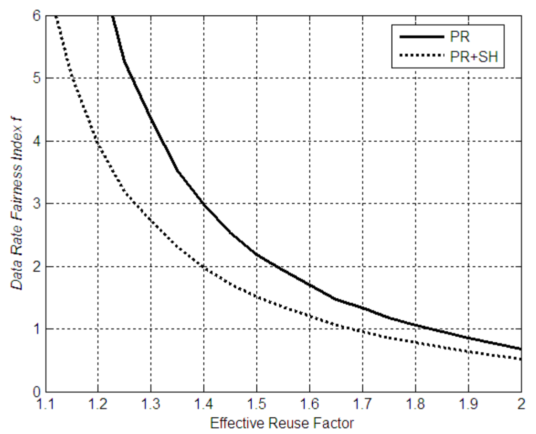


Fig. 9 Data rate fairness vs. effective reuse factor

7. Conclusions

In this paper, we proposed an inter-cell interference mitigation scheme for a multi-cell OFDMA system, and in particular we focus on downlink transmission. The basic idea of the proposed scheme is to dynamically choose between a partial frequency reuse scheme (with a reuse factor of 3) and a soft handover scheme to provide better signal quality for cell edge users. Our simulation results show that compared with standard partial frequency reuse scheme, the proposed scheme helps to improve the link quality and link spectral efficiency of cell edge users. By using our approach, there is a significant cell edge throughput gain over the standard partial frequency reuse scheme and it introduces a relatively low soft handover overhead. Considering data rate fairness among users, the proposed hybrid method also outperforms the standard partial frequency reuse scheme in total cell throughput. Therefore, we conclude that the proposed scheme is a competitive choice to enhance cell edge bit rate and overall system capacity.

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