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參加國際學術會議 IEEE WCNC 2015 發表論文

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摘要

國際電子電機工程學會無線通訊與網路研討會(IEEE Wireless Communications and Networking Conference (WCNC)) 是網路通訊領域中世界級的國際學術研討會，每年平均會有千名國際通訊專家、學者投稿。此研討會在無線網路、行動系統、及無線通訊技術發展扮演了十分重要的角色。

本次藉由科技部計劃及暨南大學的補助經費參與此一通訊網路技術交流盛會，並在其中以口頭報告介紹本實驗室的在節能無線網路佈建方法方面的研究成果。整個參與研討會的過程，不論是在一開始的論文投稿及審查委員意見、會議過程中口頭報告、大會的專題演講、以及聆聽其他專家的各種前瞻通訊技術論文發表，與國際專家學者的交流，都學到了許多極爲珍貴的經驗。也瞭解了現今國際上通訊技術研究發展方向，拓展了研究視野。

目次

一、 參與研討會目的

此次 IEEE WCNC 大會主要探討下一世代的行動通訊技術，也就是 5G 通訊系統。會議重點在於 Giga-bps 級的無線通訊系統、節能技術、以及更有效率動態使用的感知網路。5G 技術應用、物聯網、車輛通訊、感測網路、雲端服務等議題也是大會討論的重點。參與此重要通訊網路技術研討會，首要目的是發表科技部計畫研究成果論文 ”Joint Power Assignment and Relay Location Design for Cooperative Power-efficient Networks with Adaptive Transmission Mode Selection”，藉此與各國的專家學者交流。此論文與大會的容量提升、節能主題十分吻合。論文主要是探討在協力式通訊系統中，結合地設計傳輸功率與中繼站位置，達成節省功率及提升容量之雙重目的。除了發表論文，也參與了各種前瞻通訊技術論文的發表和討論，以瞭解通訊網路技術之發展現況及趨勢及脈動，並思考未來研究主題。

二、 研討會過程

本屆 IEEE WCNC 國際學術研討會於 2015 年三月九日至十二日在美國 New Orleans 舉行，爲期四天。IEEE WCNC 有爲數眾多世界各地的專家、學者投稿參與。本屆的 IEEE WCNC 會議共有 1000 篇論文投稿，收錄了 390 篇會議論文。論文發表主要區分成 PHY、MAC、Network、Service & application 等四個研究主類別 (Technical Tracks)。大會所關注的議題與個人之無線通訊網路領域之研究議題極爲相關，因此聆聽了許多場次的論文發表與討論，包括有下列議題的論文:

(1) Multihop and cooperative communications
(2) MAC for mesh, ad hoc, relay, and sensor networks
(3) Radio resource management and allocation, scheduling
(4) Cognitive and cooperative MAC
(5) Cross-layer design
(6) Wireless MAC protocols: design and analysis
(7) QoS provisioning in MAC
(8) Mesh, relay, sensor and ad hoc networks

(9) Capacity, throughput, outage, coverage

從大會議題及所收錄的論文中也可以發現幾點: 一、由於頻譜有限，爲了達成 5G 行動通訊系統 Giga-bps 級的系統容量，下世代通訊網路將會是個異質型無線系統，小細胞、D2D 通訊、協力通訊、感知無線電等各種的技術，將會在一個系統中同時並存。藉由重複使用頻譜，增強頻譜使用效率。二、由於是異質無線通訊系統，減少或控制干擾、無線電資源管理、服務品質保證仍將會是主要的技術議題。三、強調節能、低功耗的綠色通訊網路設計，也是下世代通訊技術的發展主軸。不僅是傳輸功率分配、用戶端的省電方法設計、系統佈建、或是系統架構方面的節能設計都極重要。

參與大會的兩場 Keynote speeches，分別是 Mr. Seizo Onoe (Board of Director, NTT DOCOMO) 主講的 “5G and Beyond”。演講中以日本行動通訊系統營運爲例，顯示平均每十年就會有一次通訊系統世代的演進。通訊技術的演進主要是 1 G FDMA、2G TDMA、3G WCDMA、4G OFDMA。至於目前正期待 2020 年的 5G 則是未知，或許沒有一種單一技術可代表 5G 系統，可能會是混合、或是多種技術相結合在一起的系統。以達成服務品質 RAN Latency < 1 ms 的要求。此外，在 5G 系統中，也需要關注 Internet of Things 所造成的影響。演講中，Mr. Seizo Onoe 也提出一個的觀點，並且非常自豪地強調這是在前一天自己加入的投影片，沒有其他人用過相同的方式呈現。投影片以一個傾斜的天平代表 5G 系統將會是偏重生態系(Ecosystem)，而不是技術(Technology)。並且也點出 NGMN 對 5G 的看法 “5G is an end-to-end ecosystem to enable a fully mobile and connected society”。更進一步說明了 5G 系統中，“Technologies are required to support the ecosystem and business.” 也就是期望透過現有或是新興的各種技術，相互合作，讓用戶在系統中皆有一致的體驗(即使不斷移動到不同的位置)。Mr. Seizo Onoe 也以三國演義的”分久必合，合久必分”的概念，說明現在的 4G、5G 或許比較是通訊技術合併統整的階段，但展望未來的 6G 可能會是多種技術百家爭鳴的時代。此外，整個演講中也不斷強調 NTT DOCOMO 的觀點，認爲 5G 系統應該是個全區域高速通訊的系統，而不是以 Hot Spot (熱點)型式的系統。此外，也參與 Kevin Jou (MediaTek Inc.) 主講的 “A Look at Trends in Mobile Computing”，其中是說明智慧手機的技術發展趨勢。包含”Context

Awareness”，讓智慧手機能夠智慧地學習用戶的習慣。據此，手機能提供更個人化、更貼心的服務。”Aggregation of functions across devices”的概念，則是讓手機設備能相互連接，提供不同的功能。另外，也說明 Heterogeneous Computing 的作法，在裝置內整合 CPU 與 GPU，利用 GPU 的運算性能輔助 CPU，加強整體處理能力。最後，也展示了一個非常有趣的功能。過去，手機照相有影像美化的功能。現在隨著處理器計算能力增強，手機也提供了”視訊即時美化”的能力。此展示引起極大的回響。

會議規模相當大，每個研究主類別在三月十日至三月十二日三天都安排有論文發表。論文發表的時程每天從 11:00 到 17:30，有三個時段。同一個時段，平均有八個 Sessions 同時進行。我們的論文發表安排在最後一天，三月十二日下午第一個時段 MAC-11: Relaying in Wireless Networks 場次。從兩點開始，共九十分鐘。共有五篇論文發表，平均每篇論文的時間爲十八分鐘。該場次的會議主持人爲交通大學高榮宏教授，在會議開始前便與會議主持人簡短、愉快的彼此介紹。我們是第二篇論文，全程利用投影片，以英文口頭簡報了我們的論文。由於是最後一天下午，整個大會人數明顯較少，我們場次約有十五位專家學者、學生參加。整個發表過程十分順利。

三、 心得與建議

此次會議在新奧爾良 Hilton New Orleans Riverside 飯店舉行，有來自世界各地的專家、學者、學生與會。除了參與大會主題演講和發表個人論文之外，也參與相關研究領域的論文發表場次，包括: LTE/LTE-Advanced、Cognitive Radio、Device-to-Device Communication、Relaying、Cellular Networks 等。大部分是屬於 MAC 研究類別，其中有一場參加的是屬於 PHY 研究類別，清楚感受到不同研究類別所探討的問題、及論文發表的方式都有非常大的差異。在參與其他專家學者的論文發表及討論中，也不斷思考個人目前的研究有沒有值得延伸的部分，以及未來的可能研究方向。從大會議題以及論文發表中發現，異質網路、節能、及各種網路的資源管理，例如 Femtocell 及 D2D 異質共存、或是 MTC、Clouding System 的資源管理等都是重要議題。並且，各種形式的無線通訊系統，不論是 Relay、Cooperative、 Cognitive 等系統的節能設計議題也十分重要。此外，也發現不論是何種議題，有一個重要的共通點就是”最佳化設計”。這點與個人的研究主軸相同，但目前比較是使用軟體程式庫所提供的最佳化功能去尋找最佳解。未來將會更多思考提出一些簡化的演算法，以快速的求得還不錯的次佳解。

在會議中，也發現許多論文是由碩士生發表。特別是亞洲國家的學生，有的是同系的幾個碩士生一起自己來美國。可以感覺出使用英文報告對碩士生是不容易，但卻是極爲珍貴的經驗。這點十分值得我們學習，將多多鼓勵博、碩士生可以把握機會多多歷練。

綜言之，參與此次大會，一方面可以與各地專家學者交流，另一方面也能靜下心來思考研究方向。各方面收穫十分豐富，也期許自己能多把握機會參加如此有意義的國際學術研討會。

致謝:

IEEE　WCNC 是一個重要的國際學術研討會。能夠參與此一通訊領域的重要會議，發表個人的研究成果，並與世界級專家學者交流，加深加寬了研究視野，也盼望能為台灣的研究出點微薄之力。非常感謝科技部和暨南大學在經費上的支持。

參考文獻:

Jane-Hwa Huang and Sz-Yan Hsu, “Joint Power Assignment and Relay Location Design for Cooperative Power-efficient Networks with Adaptive Transmission Mode Selection”, Proceedings of the IEEE Wireless Communications and Networking Conference, March 2015.

附件一、發表論文摘要

具備動態傳輸模式選取機制之協力節能網路中
傳輸功率與中繼站位置結合設計

Joint Power Assignment and Relay Location Design for Cooperative Power-efficient Networks with Adaptive Transmission Mode Selection

Jane-Hwa Huang and Sz-Yan Hsu

Abstract

Cooperative transmission is a power-efficient transmission technique, with the advantages of diversity and short-range communications. In this paper, we develop joint transmission power and relay location design for the cooperative networks. We investigate the impacts of transmission (TX) mode, transmission power, and relay location on the capacity and power consumption. Besides, we develop TX-mode adaptation schemes for the users to adaptively select a proper TX mode among the direct, relay, and cooperative TX modes. To achieve the goals of saving power and enhancing capacity, we propose an optimization approach to jointly determine the optimal relay location and transmission power of BS and RS; aiming to maximize power efficiency under the cell capacity and link reliability requirements. We compare the scheme with joint power and relay location design, and the schemes with only transmission power or relay location design. Simulation results show that the scheme with joint optimal design can significantly enhance the power efficiency, compared to the other two design schemes. We compare the throughput-oriented and signal-strength-oriented TX-mode selection rules. It is shown that the throughput-oriented TX-mode adaptation schemes outperform the signal-strength-oriented schemes.

Keywords: Power Efficiency, Relay location design, Power assignment, Cooperative networks.

Joint Power Assignment and Relay Location Design for Cooperative Power-efficient Networks with Adaptive Transmission Mode Selection

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***Abstract*—Cooperative transmission is a power-efficient transmission technique, with the advantages of diversity and short-range communications. In this paper, we develop joint transmission power and relay location design for the cooperative networks. We investigate the impacts of transmission (TX) mode, transmission power, and relay location on the capacity and power consumption. Besides, we develop TX-mode adaptation schemes for the users to adaptively select a proper TX mode among the direct, relay, and cooperative TX modes. To achieve the goals of saving power and enhancing capacity, we apply an optimization approach to jointly determine the optimal relay location and transmission power of BS and RS; aiming to maximize energy efficiency under the cell capacity and link reliability requirements. We compare the scheme with joint power and relay location design, and the schemes with only transmission power or relay location design. Simulation results show that the scheme with joint optimal design can significantly enhance the energy efficiency, compared to the other two design schemes. We compare the throughput-oriented and signal-strength-oriented TX-mode selection rules. It is shown that the throughput-oriented TX-mode adaptation schemes outperform the signal-strength-oriented schemes.**

I. Introduction

The cooperative network is an economical solution to enable green wireless networks [1]-[3]. Figure 1 illustrates the architecture of a cooperative power-efficient network. The user can communicate with the base station (BS) via the one-hop direct transmission (TX) mode; or receive the data forwarded from the relay station (RS) by the two-hop relay or cooperative TX mode. The cooperative network has the advantages of low cost and low power. First, avoiding the time-consuming cabling engineering work between BS and RS, the low-cost RSs can be rapidly deployed to extend coverage. Second, thanks to shorter communication distances, the two-hop communication can adopt lower transmission power.

However, saving power and enhancing capacity may be two contradictory goals. In cooperative networks, the capacity and power consumption both are affected by the TX mode, relay location, and transmission power. For the purpose of saving power, we can reduce power consumption, by adopting the two-hop cooperative TX mode to decrease the transmission distance. However, using the cooperative TX mode may decrease the capacity due to two transmission phases. For enhancing capacity, we can improve the relay link capacity, by deploying the RS near the BS. However, with a longer hop distance between RS and the user, the RS should increase transmission power to ensure the users' signal quality. In result, the power consumption may increase. Therefore, the key issues in cooperative power-efficient networks are how

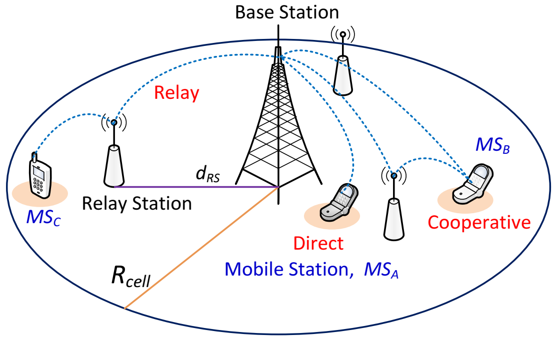

Fig. 1. Two-hop cell architecture of a cooperative relaying network.

to select the TX mode and jointly design relay location and transmission power, to save power and enhance capacity.

This paper investigates the joint transmission power and relay location design, to achieve the goals of saving power and enhancing capacity in the cooperative power-efficient networks. We develop the TX-mode adaptation schemes. According to signal strength and throughput, each user adaptively selects the proper TX mode among the direct/relay/cooperative TX modes. To achieve the optimal tradeoff between energy efficiency and capacity, we apply an optimization approach to maximize energy efficiency under the constraints of cell capacity and link reliability. We compare three design schemes: the scheme with optimal power and relay location design, that with only power assignment, and that with only relay location design. We also develop the throughput-oriented (TO) and signal-strength-oriented (SSO) TX-mode selection schemes. The TO scheme aims to adopt the TX mode with higher throughput for the user. As to the SSO scheme, it will select the cooperative TX mode, if the RS can provide stronger signal strength for the user. Besides, we investigate the impact of the number of RSs on power consumption.

In the literature, the system design issues for the cooperative power-efficient networks have been studied in two directions: relay deployment and power allocation. The works in [4]-[7] mainly investigated the optimal relay location to maximize system capacity. The authors in [4] analytically derived the optimal relay location in a one-dimension cell. [5]-[7] considered the relay deployment problem in the two-dimension cell. The authors in [5] proposed an optimization approach to determine the relay location, and compared different TX-mode selection principles. To simplify the relay deployment problem, [6] developed a Lagrangian relaxation iterative algorithm, where assumed that the RSs are placed at the specified grid points. The authors in [7] developed an efficient heuristic algorithm to design the locations of multiple relays.

In [8]-[11], the authors mainly focused on the power allocation problem, with the objective of maximizing energy efficiency. The authors in [8] investigated the OFDMA subcarrier power allocation problem under the total power and

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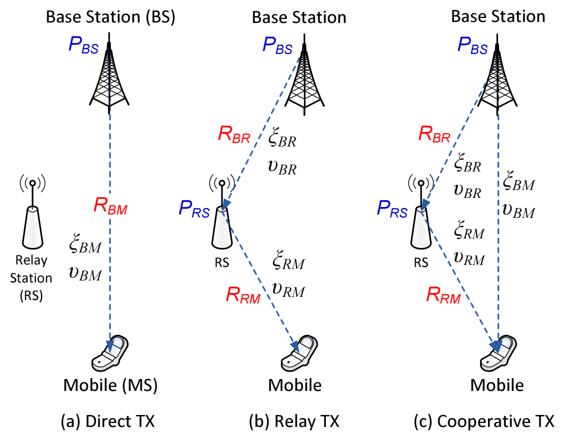

Fig. 2. Three types of transmission (TX) modes: (a) direct, (b) simple relaying, and (c) cooperative relaying TX modes.

minimal rate requirements, in a three-node relay network with a source, a relay, and a destination. The authors in [9], [10] considered user cooperation, that is, the source can select several neighboring users acting as the relays to help forward data. Then, the works investigated power allocation for source and multiple relays. [10] investigated a multiobjective optimization problem, aiming to maximize total rate and minimize total transmission power at the same time. The authors in [11] suggested that the uplink and downlink of a user can adopt different TX modes, to reduce the users' transmit power.

Fewer papers have considered joint effects of relay location, power assignment, and TX-mode adaptation on energy efficiency and cell capacity. The works in [4]-[7] mainly focused on the joint effects of relay location and TX-mode adaptation on the capacity. In contrast, the works in [8]-[10] mainly investigated the effect of power allocation on energy efficiency.

The rest of this paper is organized as follows. Section II describes the system models. In Section III, we perform joint design for relay location and transmission power, to achieve the optimal tradeoff between power saving and capacity. Section IV elaborates the resource management schemes and adaptive transmission mode selection principles. Section V evaluates the major performance metrics. Performance evaluations are shown in Section VI. Concluding remarks are given in Section VII.

II. System Models

A. Cooperative Power-efficient Network

Figure 1 shows the considered cooperative network architecture. The coverage radius of base station (BS) is R_{cell}. The relay stations (RSs) are regularly deployed around the BS, with the separation distance d_{RS} between BS and RS. There are N mobile stations (MSs) spatially uniformly distributed within the cell.

As shown in Fig. 2, the MS can adopt the direct, simple relaying, or cooperative transmission (TX) mode. The direct TX mode has single transmission phase. The relay and cooperative TX modes need two transmission phases. The first phase is the transmission from BS to RS, and the second phase is from RS to MS. Different from the relay TX mode, the cooperative TX mode requires the MS to receive the signal from BS in the first phase. Then, by the diversity combining technique such as the maximal-ratio combining (MRC) method, the MS combines the direct BS-MS signal and the relayed RS-MS signal to improve signal quality [12], [13].

These transmission modes have different capacity and power consumption. To achieve the dual goals of saving power and enhancing capacity, each MS should adaptively select the TX mode, with the following considerations. The direct TX mode has only one transmission phase. If with a long communication distance, the direct TX mode needs higher transmission power to maintain signal strength. By contrast, with shorter hop distances, the two-hop relay and cooperative TX modes can adopt lower power to improve link reliability for the users far from the BS. Nevertheless, if having a longer two-phase transmission time, using the two-hop TX modes may decrease capacity. As for the cooperative TX mode, it has better link reliability than the relay TX mode. However, to facilitate the MRC method to combine signals, the first and second phases in the cooperative TX mode usually adopt the same data rate, according to the signal strength of the weaker link [12], [13]. Since $R_{BR} = R_{RM}$ in Fig. 2 (c), the cooperative TX mode may have lower throughput than the relay TX mode, even with higher link reliability.

B. Radio Channel Effects

We consider the radio propagation effects, including path loss, shadowing, and multipath fading.

1) Path Loss: According to the channel model for relay systems [14], the path loss $L(d)$ (dB) from the transmitter to the receiver at the propagation distance d is modeled as

$$L(d) = \begin{cases} 20\log_{10}(\frac{4\pi d}{\lambda}), & \text{for } d \leq d_0' \\ A + 10\epsilon\log_{10}(\frac{d}{d_0}) + L_{f_c} + L_{h_r}, & \text{for } d > d_0' \end{cases} \quad (1)$$

where λ is the wavelength in meter, $d_0 = 100$ (m) is a reference distance. ϵ, d_0', A, L_{f_c}, and L_{h_r} are the parameters depending on propagation environment, as defined in [5], [14].

2) Shadowing: The shadowing effect is modeled by a log-normal random variable $10^{\xi/10}$. ξ is a Gaussian-distributed random variable with zero mean and the standard deviation σ. The probability function density (pdf) is defined as

$$f_\xi(\xi) = \frac{1}{\sqrt{2\pi}\sigma}\exp(-\frac{\xi^2}{2\sigma^2}) \ . \quad (2)$$

3) Multipath Fading: The Rayleigh multipath fading is modeled by an exponentially-distributed random variable υ, with the pdf defined as $f_\upsilon(\upsilon) = e^{-\upsilon}$.

Under the impacts of path loss, log-normal shadowing, and Rayleigh fading, the received SNR γ is given as

$$\gamma = \frac{P_{tx}L(d)^{-1}10^{\xi/10}\upsilon}{N_0} \quad (3)$$

where assume transmit power P_{tx} and noise power N_0.

III. Energy Efficiency Maximization

In cooperative networks, transmission power, relay location, and transmission mode have complicated effects on capacity and power consumption. Specifically, for saving power, we may reduce transmission power. However, reducing power may result in lower capacity. For enhancing the capacity of cell-edge users, we may deploy the RSs near cell boundary to reduce the distance of RS-MS link. Meanwhile, since the hop distance from BS to RS increases, the BS should raise power to ensure the relay link capacity between BS and RS. The power consumption may increase. The TX mode also affects capacity and power consumption, as discussed in Section II-A.

Therefore, to achieve the tradeoff between capacity and power saving, we should jointly consider power assignment,

TABLE I
MODULATION AND CODING SCHEMES (MCSS)

MCS	Modulation	Code Rate	Spectrum Efficiency χ (bits/s/Hz)	SNR Requirement (dB)
1	QPSK	1/2(4)	0.25	-2.5
2	QPSK	1/2(2)	0.5	0.5
3	QPSK	1/2	1	3.5
4	QPSK	3/4	1.5	6.5
5	16-QAM	1/2	2	9
6	16-QAM	3/4	3	12.5
7	64-QAM	1/2	3	14.5
8	64-QAM	2/3	4	16.5
9	64-QAM	3/4	4.5	18.5

relay location, and transmission mode. In this paper, we develop TX-mode selection principles in Section IV-B. Besides, we formulate a nonlinear programming optimization problem to jointly determine relay location d_{RS}, and the transmission power (P_{BS} and P_{RS}) of BS and RS. The objective function aims to maximize energy efficiency, subject to the cell capacity and link reliability requirements. Let cell capacity C be the aggregate throughput delivered from the BS to all the MSs. P_C is the average system power consumption. The energy efficiency is defined as $\eta = C/P_C$, as in [3]. The formulated optimization problem can be expressed as

$$\underset{d_{RS},P_{BS},P_{RS}}{\textbf{MAX}} \text{ Energy efficiency } \eta = \frac{C}{P_C} \tag{4}$$

$$\text{subject to:} \quad C \geq C_{req} \tag{5}$$

$$p_R \geq p_{R,req}. \tag{6}$$

In the constraints, p_R is the link reliability defined as the successful transmission probability. C_{req} and $p_{R,req}$ represent the cell capacity and link reliability requirements, respectively. C, P_C, and p_R are evaluated in Section V.

IV. RESOURCE MANAGEMENT SCHEMES

This section discusses major resource management schemes in the cooperative power-efficient networks, including rate adaptation, TX-mode selection, and time-slot allocation.

A. SNR-based Rate Adaptation

The modulation and coding scheme (MCS), and the data rate are determined according to the received SNR γ. Table I lists the considered MCSs, the SNR requirement, and the spectrum efficiency χ for each MCS [15]. According to the SNR requirement in Table I, the MS selects a proper MCS. For example, if $\gamma = 10$ dB, the MS can select the fifth MCS scheme with spectrum efficiency $\chi(\gamma) = 2$ bits/s/Hz.

Consider a generic OFDMA system of bandwidth B. Assume N_d data subcarriers and spectrum efficiency $\chi(\gamma)$ for the selected MCS. For the FFT size M, the link data rate R can be expressed as a function of received SNR γ, that is, [16]

$$R = f_{rate}(\gamma) = \frac{B}{M}\frac{N_d}{1+G} \cdot \chi(\gamma) \tag{7}$$

where G is the guard fraction. Thus, if the SNRs of BS-MS, BS-RS, and RS-MS links for an MS are (γ_{BM}, γ_{BR}, γ_{RM}), the link data rates for this MS can be determined as

$$R_{BM} = f_{rate}(\gamma_{BM}), \tag{8}$$

$$R_{BR} = f_{rate}(\gamma_{BR}), \tag{9}$$

$$R_{RM} = f_{rate}(\gamma_{RM}). \tag{10}$$

B. Adaptive Transmission Mode Selection Principles

(1) Throughput-oriented (TO) Selection Scheme: This scheme selects the TX mode having higher effective data rate, to improve throughput. First, we calculate the effective data rate for each TX mode. With only one hop, the effective date rate R_D of direct TX mode is defined as

$$R_D = R_{BM} = f_{rate}(\gamma_{BM}). \tag{11}$$

Let L_{pkt} be the packet size. For the two-hop relaying TX modes, the total two-hop transmission time is $t_{two-hop}$. The effective data rate R_{Relay} for relay TX mode can be given as

$$\begin{aligned} R_{Relay} =& \frac{L_{pkt}}{t_{two-hop}} = \frac{L_{pkt}}{\frac{L_{pkt}}{R_{BR}} + \frac{L_{pkt}}{R_{RM}}} = \left(\frac{1}{R_{BR}} + \frac{1}{R_{RM}}\right)^{-1} \\ =& \left(\frac{1}{f_{rate}(\gamma_{BR})} + \frac{1}{f_{rate}(\gamma_{RM})}\right)^{-1}. \end{aligned} \tag{12}$$

In the cooperative TX mode, assume that the MRC method is used to combine the two copies of signals. Besides, the first and second transmission phases use the same data rate, as discussed in Section II-A. Constrained by the SNR of the weaker link, the link data rates are determined by

$$R_{BR} = R_{RM} = f_{rate}\left(\min(\gamma_{BR}, \gamma_{BM} + \gamma_{RM})\right). \tag{13}$$

Then, the effective data rate R_{Coop} can be calculated as

$$R_{Coop} = \left(\frac{1}{R_{BR}} + \frac{1}{R_{RM}}\right)^{-1} = \frac{1}{2}R_{BR}. \tag{14}$$

From (12) and (14), we can observe that due to selecting the same rate for two phases, the cooperative TX mode may have lower effective data rate than the relay transmission.

The throughput-oriented selection rule selects the TX mode, according to the effective data rate. Consider a user MS_i at the position (r, θ). The links of the user suffer from independent shadowing $\boldsymbol{\xi} = (\xi_{BM}, \xi_{BR}, \xi_{RM})$ and multipath fading $\boldsymbol{\upsilon} = (\upsilon_{BM}, \upsilon_{BR}, \upsilon_{RM})$, respectively. The SNRs $(\gamma_{BM}, \gamma_{BR}, \gamma_{RM})$ and effective data rates $(R_D, R_{Relay}, R_{Coop})$ can be obtained by (7)-(14). According to the TO selection rule, the effective data rate for this MS is equal to

$$R_e(r, \theta, \boldsymbol{\xi}, \boldsymbol{\upsilon}) = \max(R_D, R_{Relay}, R_{Coop}). \tag{15}$$

(2) Signal-strength-oriented (SSO) Selection Scheme: In this scheme, the MS selects the two-hop transmission, if the received signal strength from RS is stronger than that from BS. Besides, since the cooperative TX mode has higher SNR than the relay TX mode, the MS will adopt the cooperative TX mode rather than the relay TX mode. Hence, the effective data rate is equal to

$$R_e(r, \theta, \boldsymbol{\xi}, \boldsymbol{\upsilon}) = \begin{cases} R_{Coop}, & \gamma_{RM} \geq \gamma_{BM} \\ R_D, & \text{otherwise.} \end{cases} \tag{16}$$

C. Equal Time-duration Slot Allocation

In this network, each MS is allocated with the same fraction of time for transmission, regardless of the adopted TX mode. Assume the average effective data rate R_e of one MS as in (22). Since N users evenly share the time resource, the average per-user throughput is $C_{user} = R_e/N$.

V. SYSTEM PERFORMANCE

A. Link Reliability

The link reliability is defined as the probability that the received SNR γ is greater than a predefined threshold z_{th}. Without loss of generality, we assume that if the SNR γ is greater than z_{th}, the transmission is successful. If $\gamma < z_{th}$, the transmission is failed; and the spectrum efficiency $\chi(\gamma)$ and the link data rate $f_{rate}(\gamma)$ are both zero.

To begin with, we discuss the successful transmission condition for each TX mode. For the direct transmission, the condition of reliable transmission is $S_D = \{\gamma_{BM} \geq z_{th}\}$. Thus, under the impacts of shadowing ξ_{BM} and fading υ_{BM}, the link reliability $p_{R,D}$ of direct TX mode is defined as

$$p_{R,D} = \Pr(S_D) = \Pr[\gamma_{BM} \geq z_{th}] = \Pr\left[\frac{P_{tx}L(d_{BM})^{-1}10^{\xi_{BM}/10}\upsilon_{BM}}{N_0} \geq z_{th}\right] \quad (17)$$

where d_{BM} is the propagation distance from BS to MS. In the relay TX mode, since both two transmission phases should be successful, the successful transmission condition is given as

$$S_{Relay} = \{(\gamma_{BR} \geq z_{th}) \cap (\gamma_{RM} \geq z_{th})\}. \quad (18)$$

In the cooperative TX mode, the data can be successfully delivered to the MS via the direct BS-MS link or the two-hop BS-RS-MS link. Accordingly, the successful transmission condition is expressed as a union, that is,

$$S_{Coop} = \{[\gamma_{BM} \geq z_{th}] \cup [(\gamma_{BR} \geq z_{th}) \cap (\gamma_{RM} + \gamma_{BM} \geq z_{th})]\}. \quad (19)$$

In (19), the first event means successful transmission from BS to the user. The second event represents successful transmission by the two-hop cooperative communication.

Since the MS can adaptively select the direct, relay, or cooperative TX mode, the successful transmission condition can be expressed as the union $S_{Adaptive} = \{S_D \cup S_{Relay} \cup S_{Coop}\}$. Besides, the overall link reliability p_R is defined as

$$p_R = \Pr(S_{Adaptive}) = \Pr\left[S_D \cup S_{Relay} \cup S_{Coop}\right]. \quad (20)$$

B. Capacity

The system capacity C is defined as the aggregate throughput delivered from the BS to all the MSs. Consider a user MS_i at the position (r, θ). Assume independent shadowing $\boldsymbol{\xi} = (\xi_{BM}, \xi_{BR}, \xi_{RM})$ and multipath fading $\boldsymbol{\upsilon} = (\upsilon_{BM}, \upsilon_{BR}, \upsilon_{RM})$ in the BS-MS/BS-RS/RS-MS links of the user. After the MS adaptively selects the TX mode, the effective data rate for the MS is $R_e(r, \theta, \boldsymbol{\xi}, \boldsymbol{\upsilon})$, as discussed in Section IV-B. By averaging over $\boldsymbol{\xi}$ and $\boldsymbol{\upsilon}$, the average effective data rate $R_e(r, \theta)$ for the user can be calculated as

$$R_e(r,\theta) = \int_{-\infty}^{\infty}\int_{0}^{\infty} R_e(r,\theta,\boldsymbol{\xi},\boldsymbol{\upsilon}) f_{\boldsymbol{\xi}}(\boldsymbol{\xi}) f_{\boldsymbol{\upsilon}}(\boldsymbol{\upsilon}) d\boldsymbol{\upsilon} d\boldsymbol{\xi}. \quad (21)$$

Suppose that the MS are spatially uniformly-distributed within the cell of radius R_{cell}. The pdfs of the distance (r) and angle (θ) between the BS and the MS are expressed as $f_r(r) = 2r/R_{cell}^2$ and $f_\theta(\theta) = 1/2\pi$. Then, the overall average effective data rate R_e of one MS can be calculated as

$$R_e = \int_0^{2\pi}\int_0^{R_{cell}} R_e(r,\theta) f_r(r) f_\theta(\theta) dr d\theta = \int_0^{2\pi}\int_0^{R_{cell}} R_e(r,\theta)\left(\frac{r}{\pi R_{cell}^2}\right) dr d\theta. \quad (22)$$

TABLE II
SYSTEM PARAMETERS

Item	Nominal Value
Carrier frequency (f_c)	2.5 GHz
System bandwidth (B)	10 MHz
OFDM FFT size (M)	1024
Data subcarriers (N_d)	720
Guard fraction (G)	1/8
Cell radius (R_{cell})	1500 m
Number of relay stations	8
Antenna heights of BS, RS, and MS	$(30, 15, 2)$ m
Number of users (N)	30
Link reliability constraint ($p_{R,req}$)	0.9
Cell capacity requirement (C_{req})	15 Mbps
SNR threshold (z_{th})	-2.5 dB
Standard deviation (σ)	6 dB
Noise power (N_0)	-102 dBm

Because of equal-duration time slots for N MSs, user throughput is $C_{user} = R_e/N$ and cell capacity is $C = NC_{user} = R_e$.

C. Energy Efficiency

The direct, relay, cooperative TX modes have different power consumption. Let P_{BS} and P_{RS} be the transmission power of BS and RS, respectively. For the one-hop direct TX mode, the power consumption is $P_{C,D} = P_{BS}$. In the relay TX mode, the first and second phases have different data rates and transmission time. Thus, the average power consumption $P_{C,Relay}$ is calculated as

$$P_{C,Relay} = P_{BS}\frac{\frac{L_{pkt}}{R_{BR}}}{\frac{L_{pkt}}{R_{BR}} + \frac{L_{pkt}}{R_{RM}}} + P_{RS}\frac{\frac{L_{pkt}}{R_{RM}}}{\frac{L_{pkt}}{R_{BR}} + \frac{L_{pkt}}{R_{RM}}} = \frac{P_{BS}R_{RM} + P_{RS}R_{BR}}{R_{BR} + R_{RM}}. \quad (23)$$

In the cooperative TX mode, the first and second phases adopt the same data rate, and thus have the same transmission time. The average power consumption $P_{C,Coop}$ is given as

$$P_{C,Coop} = \frac{1}{2}(P_{BS} + P_{RS}). \quad (24)$$

After the MS adaptively selects the TX mode, the power consumption for one user is given as

$$P_C(r,\theta,\boldsymbol{\xi},\boldsymbol{\upsilon}) = \begin{cases} P_{C,D}, & \text{if selecting direct mode} \\ P_{C,Relay}, & \text{if selecting relay mode} \\ P_{C,Coop}, & \text{if selecting cooperative mode.} \end{cases} \quad (25)$$

The energy efficiency η is the achievable cell capacity per unit of power, which is defined as the ratio of cell throughput C to the overall system power consumption P_C [3]. That is,

$$\eta = \frac{C}{P_C} = \frac{C}{\int_0^{2\pi}\int_0^{R_{cell}} P_C(r,\theta) f_r(r) f_\theta(\theta) dr d\theta} \quad (26)$$

where $P_C(r,\theta) = \int_{-\infty}^{\infty}\int_0^{\infty} P_C(r,\theta,\boldsymbol{\xi},\boldsymbol{\upsilon}) f_{\boldsymbol{\xi}}(\boldsymbol{\xi}) f_{\boldsymbol{\upsilon}}(\boldsymbol{\upsilon}) d\boldsymbol{\upsilon} d\boldsymbol{\xi}$.

VI. SIMULATION RESULTS

In this section, we investigate the impacts of TX-mode adaptation, transmission power, and relay location on cell capacity and energy efficiency in the cooperative power-efficient networks. We compare the scheme with joint power and relay location design, and the schemes with only transmission power or relay location design. Besides, we compare three TX-mode adaptation schemes: the D/R/C, D/R, and D/C schemes. In the D/R/C adaptation scheme, the MS can adaptively select one from the direct/relay/cooperative TX modes. In the D/R scheme, the MS can select the direct or relay TX mode. The D/C scheme selects between the direct and cooperative TX

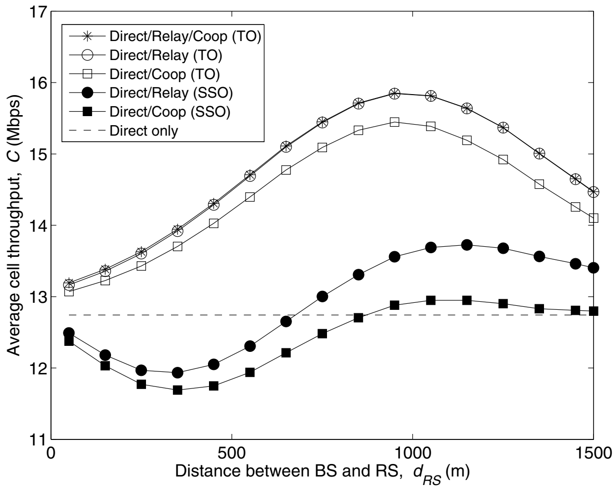

Fig. 3. Cell capacity C versus the relay location d_{RS} under various TX-mode adaptation schemes, for the given power of BS and RS.

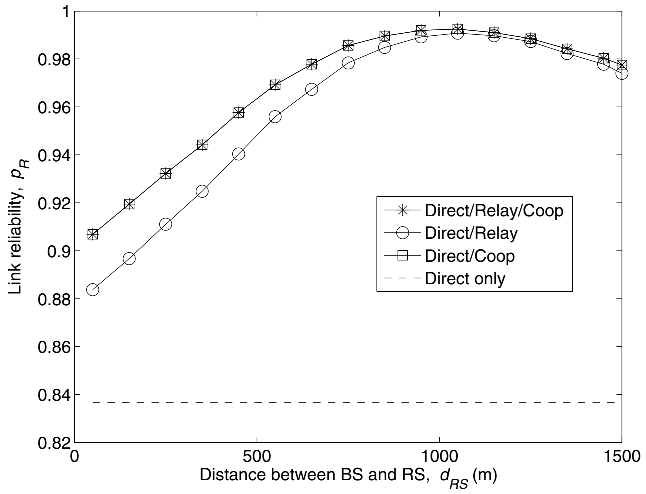

Fig. 4. Link reliability p_R versus the relay location d_{RS} under various TX-mode adaptation schemes, for the given power of BS and RS.

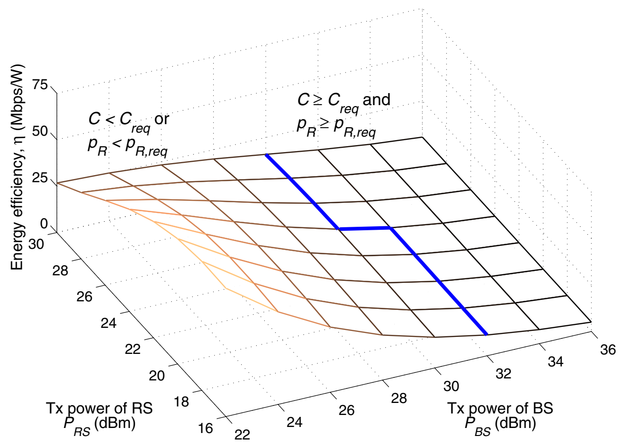

Fig. 5. Energy efficiency η versus the power of BS and RS in the throughput-oriented D/R/C adaptation scheme, for the given relay location $d_{RS} = 750$ m.

modes. We consider the throughput-oriented (TO) and signal-strength-oriented (SSO) TX-mode selection rules. By the SSO rule, the D/R/C scheme will select only between the direct and cooperative TX modes, as discussed in Section IV-B. Thus, in the SSO rule, we only compare the D/C and D/R adaptation schemes. We apply the active-set algorithm to find the optimal parameters for the constrained nonlinear optimization problem in (4). The system parameters are listed in Table II. Assume cell radius $R_{cell} = 1500$ (m) and $N = 30$ active users. We consider the cell capacity and link reliability requirements, $C_{req} = 15$ Mbps and $p_{R,req} = 0.9$, as an example. The system parameters and performance requirements may vary for different systems. However, the developed optimization approach is general enough for different cooperative networks with various performance requirements.

Figure 3 illustrates the cell capacity C against the relay location d_{RS}, for various TX-mode adaptation schemes with the fixed transmission power $(P_{BS}, P_{RS}) = (30, 27)$ dBm. Obviously, the throughput-oriented TX-mode adaptation schemes significantly improve cell capacity. In this example, at the optimal relay location $d_{RS} = 950$ (m), the throughput-oriented D/R/C adaptation scheme can improve cell capacity by 24% over the direct-only scheme. Among the TO adaptation schemes, the D/R/C scheme can achieve the best cell capacity. The D/C scheme has lower cell capacity since two phases in the cooperative TX mode select the same link data rate. Besides, due to different link data rates for the first and second phases, the relay transmission usually has higher effective data rate. In most cases, the TO D/R/C scheme actually will select the relay TX mode rather than the cooperative TX mode. Hence, the D/R scheme can achieve comparable cell capacity as the D/R/C scheme.

In Fig. 3, the SSO adaptation schemes may yield lower cell capacity than the direct-only scheme. This is because the SSO selection rule adopts the two-hop TX modes if the RS provides stronger signal strength. For the MS at the region between BS and RS, the MS may still choose the two-hop TX modes, even if the direct TX mode can achieve higher throughput. Thus, the SSO schemes have lower cell capacity. As for the TO selection rule, it adopts the two-hop TX modes, only if the RS can help improve the effective data rate. Therefore, the TO adaptation schemes have higher cell capacity than the SSO schemes.

Figure 4 depicts the link reliability p_R against the relay location d_{RS}, for various TX-mode adaptation schemes at the given power $(P_{BS}, P_{RS}) = (30, 27)$ dBm. Because the TX-mode selection rule is to select one from the TX modes being able to successfully deliver data, the selection rule will not impact link reliability. Clearly, the TX-mode adaptation schemes can achieve higher link reliability than the direct-only scheme. Besides, with the option to select the cooperative TX mode, the D/R/C and D/C schemes have better link reliability.

Figure 5 shows the energy efficiency versus the transmission power of BS and RS, under the throughput-oriented D/R/C adaptation scheme at the given relay location $d_{RS} = 750$ (m). Obviously, if the transmission power is reduced, the energy efficiency can be significantly improved. However, the cell capacity and link reliability requirements may be not met. For example, if the transmission power (P_{BS}, P_{RS}) decrease from (36,30) to (22,16) dBm, the energy efficiency remarkably increases from 5.3 to 69.1 Mbps/W. Meanwhile, since cell capacity and link reliability are degraded to 8.9 Mbps and 0.84, the requirements are not met.

Figures 3-5 demonstrate that relay location, and transmission power all significantly affect cell capacity, link reliability, and energy efficiency. Hence, we should jointly design the relay location, and the transmission power of BS and RS, as the optimization approach in (4).

Figure 6 illustrates the achieved optimal energy efficiency for various TX-mode adaptation schemes. We compare three

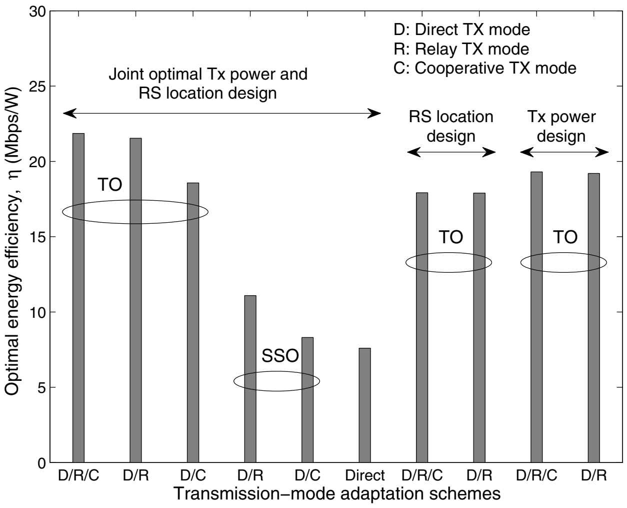

Fig. 6. Achieved energy efficiency η for various TX-mode adaptation schemes.

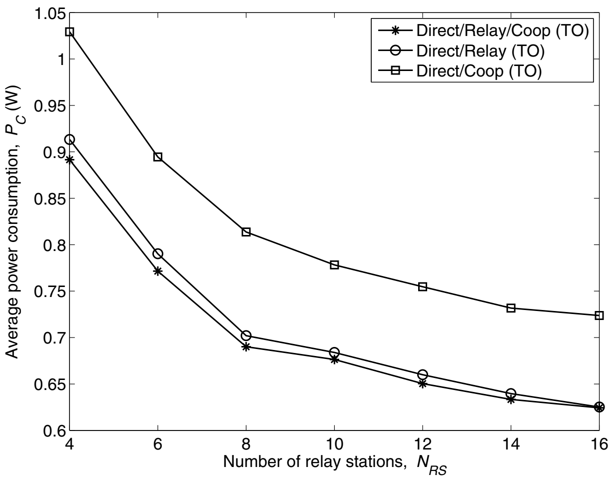

Fig. 7. Power consumption P_C versus the number of RSs for various throughput-oriented adaptation schemes, under joint optimal design.

design schemes: (1) the scheme with joint power and relay location design, (2) that with only relay location design, where (P_{BS}, P_{RS}) = $(30, 27)$ dBm; and (3) that with only power assignment, where $d_{RS} = 750$ (m). Clearly, the scheme with joint optimal design can have better energy efficiency than the other design schemes. In this example, under the TO D/R/C scheme, the scheme with joint optimal design can improve energy efficiency by 11% over that with power assignment, and by 21% over that with relay location design.

The figure also shows that the TO TX-mode adaptation schemes have better energy efficiency than the SSO schemes. Among the TO adaptation schemes, the D/R/C scheme has the best energy efficiency. Besides, the D/R and D/R/C schemes achieve comparable energy efficiency. In this example, with joint optimal design, the TO D/R/C scheme can improve energy efficiency by 288% over the direct-only scheme.

Figure 7 shows average power consumption P_C against the number of relay stations, for various TO adaptation schemes under joint optimal design. With more relay stations, since the hop distance between RS and MS decreases, the transmission power of relay station and the overall power consumption can be reduced. However, as the number of RSs is greater than eight, the reduction of power consumption gradually diminishes. In the figure, the D/R/C scheme has lower power consumption. This is because the D/R/C scheme has higher cell capacity and link reliability. Hence, it can adopt lower transmission power to meet the cell capacity and link reliability requirements.

VII. Conclusions

In this paper, we develop the joint power and relay location design for cooperative power-efficient networks. We investigate joint impacts of TX mode, transmission power, and relay location on capacity and power consumption. We also develop the throughput-oriented and signal-strength-oriented TX-mode adaptation schemes. We apply an optimization approach to jointly determine the optimal relay location and transmission power, to maximize energy efficiency subject to cell capacity and link reliability requirements. Simulation results show that the scheme with joint power and relay location design significantly enhances energy efficiency and cell capacity, compared to the schemes with only power or relay location design. Besides, under joint optimal design, the TO TX-mode adaptation schemes yield higher capacity and energy efficiency than the SSO schemes. Among the TO schemes, the D/R/C adaptation scheme achieves the best energy efficiency, because it can enhance link reliability and capacity with lower power. The R/C scheme is also a good option, because it has lower complexity and achieves comparable energy efficiency as the D/R/C scheme.

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