Survey and Analysis of Power Control for Collaborative Networks

Weisi Guo[1], Ioannis Chatzigeorgiou[1], Ian J. Wassell[1] and Rolando Carrasco[2]
[1]University of Cambridge, Computer Laboratory, Cambridge CB3 0FD, United Kingdom
Email: {wg209, ic231, ijw24}@cl.cam.ac.uk
[2]Newcastle University, School of EE&C Engineering, Newcastle-upon-Tyne NE1 7RU, United Kingdom
Email: r.carrasco@newcastle.ac.uk

***Abstract*—The aim of this paper is to first review power allocation solutions for wireless relay networks and show how channel state information (CSI) availability and system diversity are the dominant factors, as opposed to relaying protocols: i.e., amplify or decode and forward. We then introduce power allocation solutions for a cooperative network, where users act as relays for each other, and utilize powerful coding schemes. In the analysis, we compare cooperative solutions to the relaying solutions.**

I. Introduction

In wireless communications, the signal is not only corrupted by additive noise, but also attenuated by the path loss and multi-path fading effects. The challenge remains in two forms: time varying fading and interference. Traditionally, these challenges have been met by combating them with increased reliability, e.g., sophisticated coding. However, in more recent times, the solution has shifted to exploiting multi-path propagation. One such solution is to allow either relays or cooperating users acting as relays to combat fading effects. Therefore, we define a **relay network** as one where a user is assisted by multiple relays to transmit to a destination [1]. The diversity arising from the use of different fading paths can improve system performance. A **collaborative network** involve multiple cooperating users sharing information and transmitting each other's data to the destination [2], which can be seen as a more complex form of a relaying network. Fig. 1 shows a two user cooperative network.

The motivation for this paper is to review and compare existing solutions to those proposed by the authors. We hope to gain insight into how power allocation varies with a variety of system variables such as: cooperation scheme, system topology, availability of CSI and relaying protocols. In Section II, we define the system model and the channel environment, as well as various system variables. In Section III, we review existing power control solutions for relay and cooperative systems and see how they behave with different parameters. We will then introduce our own work on cooperative power control in Section IV, and compare with previous work. Our work is backed up by simulation results and closed form expressions.

This work is supported by EPSRC under Grant EP/E012108/1.

II. Cooperative System

A. Channel Model and Definitions

Most work in wireless relay and cooperative networks assume that transmissions take place over a Rayleigh block flat fading channel impaired by additive white Gaussian noise (AWGN). This is appropriate for a slowly changing environment such as that experienced in a fixed wireless access (FWA) system. Within a block period, the channel gain coefficient remains constant, and any power adaption occurs between the blocks. Such a model is more suitable for the frequency range of 2GHz, which is commonly used by current wireless technologies. At higher frequencies, the propagation paths become more correlated due to the presence of a line of sight (LOS) component, and Ricean fading maybe more applicable [3]. In this paper, we define:

- M: the total number of transmitting nodes, and thus each user can have $0 \leq m \leq M-1$ cooperating partners or relays.
- i: the ith node.
- i': another node with respect to node i ($i' \neq i$).
- $\overline{\gamma}_{i-d}$: the average SNR of the uplink channel between node i and destination d.
- $\overline{\gamma}_{i-i'}$: the average SNR of the interuser channel between node i and destination i'.
- γ: the instantaneous SNR of a channel with fading coefficient h.
- N_0: the average additive noise power.
- P: denotes the power assigned. The total power available is $P_\Sigma = P_s + P_r$, where P_s is power assigned to a transmitting source node's initial broadcast stage and P_r assigned to the secondary relaying stage.

We define a **symmetrical** system, as one where the uplink channels are statistically similar to each other ($\overline{\gamma}_{i-d} = \overline{\gamma}_{i'-d}$) [4]. Conversely an **asymmetrical** system is one where the uplink channels are different [5]. A 2 user cooperative model is demonstrated in Fig. 1. The receiver of all systems performs maximum ratio combining (MRC) of the uplink channels, unless otherwise stated.

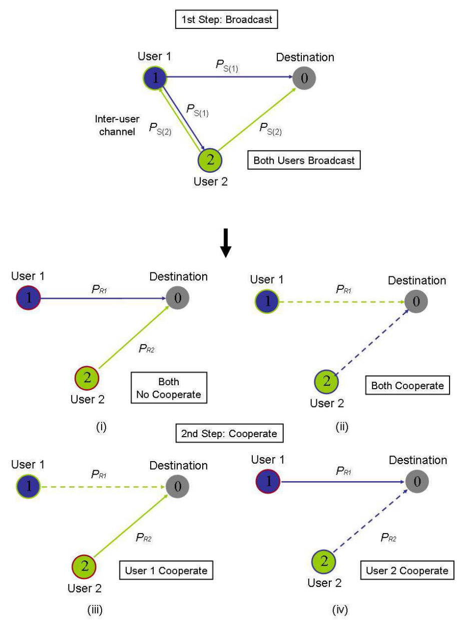

Fig. 1. The Two Steps of a Decode-and-Forward Cooperation Block for $M = 2$ Users

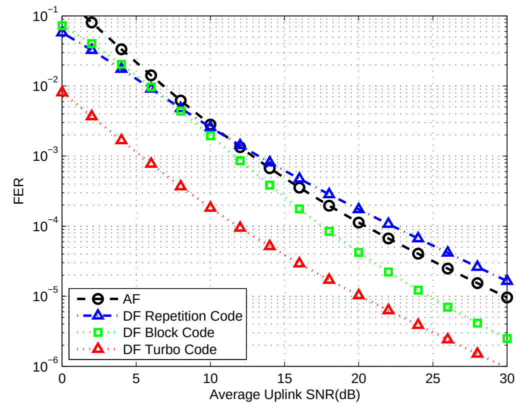

Fig. 2. Comparison of FER performance for AF; Repetition, Block and Turbo Coded DF

B. Relaying Protocol and Receiver

Generally, two types of relaying protocols are considered: those which amplify and those which decode.

Amplify and Forward (AF) is the simplest protocol to implement. It is often referred to as the non-regenerative relaying protocol. AF will amplify the received signal to counteract the inter-user channel loss, and then forward it to the receiver. At the relay, the optimal channel gain has been shown to be [1]: $\sqrt{\frac{P_s}{|h_{i-i'}|^2 P_s + N_0}}$. The performance of this protocol suffers from the fact that it also amplifies the inter-user channel noise and requires constant estimation of the interuser channel quality.

Decode and Forward (DF) is any protocol where the relay performs decoding and re-encoding before forwarding the data to the receiver, and is sometimes referred to as ”regenerative” relaying. The requirement for cooperation is that the relay successfully decodes the message from the source. For tractable expressions, a repetition code is commonly used to analyze DF protocols [6], giving it an outage performance similar to that of AF. However, more complex coding schemes can be used to significantly improve performance, which we can see from Fig. 2. Since cooperation and diversity is not assured, the analysis of DF systems without assumptions can prove to be difficult. In addition to using repetition codes, common assumptions assume that the interuser channel is perfect, either through channel inversion or with the use of wired infrastructure: i.e., optical fibre link. This effectively reduces the problem to that of a multiple input multiple output (MIMO) system, and doesn’t yield further intuition into how a cooperative system with non-perfect channels may perform.

C. Topology, Scheme and CSI

The topology of the system describes the number of relays/users and their placement. The vast majority of previous literature considers a source and destination pair, with one or more randomly placed relay nodes. Simpler considerations have relays that are placed with even distribution [7], placed with equal distance [4] [8], or placed in line [9] [10] with the source and destination. Some of these topologies are representative of a practical application, whereas others are used to simplify complex problems in order to yield intuitive and tractable solutions. User schemes, consider whether the users are willing to cooperate selfishly or unselfishly. Most previous literature has assumed that all nodes have the same agenda, which is to unselfishly boost system performance. We therefore label an **unselfish** scheme as one where nodes will always attempt to cooperate whenever possible. However, if the nodes are selfish, we define a **mutually selfish** scheme as one where node i will only cooperate with node i', if the cooperation is reciprocated (i.e., a handshake is required) [8]. We have also analyzed a leeching node, which is a node that pretends to cooperate, but in fact only transmits its own data. Analysis of the capacity gain available from power allocation in a cooperative system was performed by [11]. It was concluded that in order for power control to be significantly effective, full CSI at both the receiver and transmitter is crucial.

III. Relay Network Power Control

As mentioned previously, a relay network is composed of a single source, which is aided by multiple relay nodes. A variety of power allocation solutions are derived for systems which have varying degrees of diversity, CSI feedback, and different relaying protocols and topology. What we will show is that the form of the optimal solution depends more

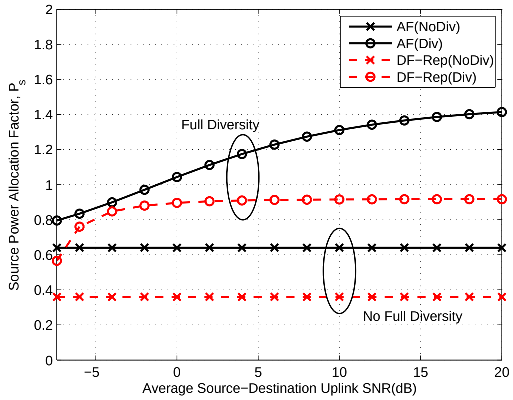

Fig. 3. Effect of Diversity on Power Allocation Factors for a Relay Network, with 5dB interuser SNR

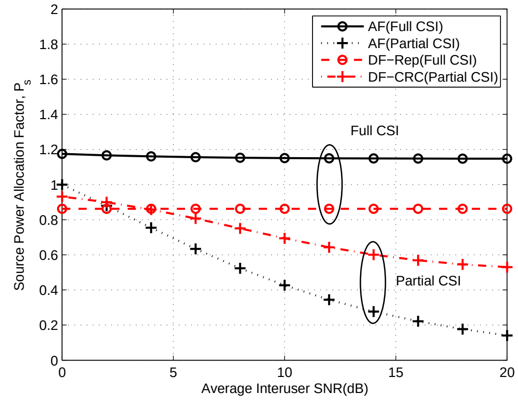

Fig. 4. Effect of CSI Availability on Power Allocation Factor for a Relay Network, with 5dB uplink SNR.

on the system diversity and CSI availability, than relaying protocol and network topology.

A. Diversity

We now look at how the power allocation solution varies with diversity order and relaying protocol. A system with full diversity is one where both the relays and direct channels are efficiently utilized to achieve the full diversity. Conversely, a system **without full diversity** is one where only the relayed paths are considered. For a two relay system without full diversity, the solution for DF relaying [12] [13] is:

$$P_s^{DF} = \frac{\sqrt{\overline{\gamma}_{i'-d}}}{\sqrt{\overline{\gamma}_{i''-d}} + \sqrt{\overline{\gamma}_{i'-d}}} P_\Sigma, \quad (1)$$

where i'' is another relay node ($i'' \neq i'$). For a single AF relay, the following solution is obtained [14]:

$$P_s^{AF} = \frac{1}{1 + \sqrt{\frac{\gamma_{i-i'} P_\Sigma + 1}{\gamma_{i'-d} P_\Sigma + 1}}} P_\Sigma. \quad (2)$$

For a DF system with **full diversity**, the analysis is non-trivial, especially for MRC receivers. In [15] an approximation is made, whereby the receiver is said to only receive the signal correctly, if both the relayed and direct signals are coherently detected. Under such a scheme, the optimal power allocation is:

$$P_s^{DF} = \frac{\sqrt{\overline{\gamma}_{i'-d}}}{\sqrt{\overline{\gamma}_{i-i'}} + \sqrt{\overline{\gamma}_{i'-d}} - \sqrt{\overline{\gamma}_{i-d}}} P_\Sigma. \quad (3)$$

By using selection combining, rather than maximum ratio-combining at the receiver the problem can be solved. The resulting optimal power allocation for a selecting combining DF system is [12]:

$$P_s^{DF} = \frac{P_\Sigma}{1 + \left(\frac{\overline{\gamma}_{i''-d}}{\overline{\gamma}_{i'-d}} + \frac{\overline{\gamma}_{i''-d}\left(1 - e^{T\left(\frac{1}{\overline{\gamma}_{i'-d}} + \frac{1}{\overline{\gamma}_{i''-d}}\right)}\right)}{\overline{\gamma}_{i-d}\left(e^{\frac{T}{\overline{\gamma}_{i-d}}} - 1\right)}\right)^{-\frac{1}{2}}}, \quad (4)$$

where T is the SNR threshold, operating below which an outage occurs. For equal comparison with schemes later on, we use $-4.4dB$ in simulations. We can see that (4) can be reduced to (1), if the direct path SNR ($\overline{\gamma}_{i-d}$) is set to zero. This can be seen in Fig. 3, where at low source-destination SNR, the diversity solution begins to fall to the no diversity solution. We have plotted *DF-Rep(NoDiv)* (1), *AF(NoDiv)* (2), *DF-Rep(Div)* (4) and *AF(Div)* which is only available as an iterative numerical form [12]. The above solutions can be summarized by Fig. 3, where we can see that a system without full diversity does not factor the direct channel into its power allocation solution. A full diversity system requires a higher transmit power from the source to both the direct and interuser channels, but also places increased emphasis on direct transmission as the direct channel improves.

B. CSI

A system is said to have full CSI when both the transmitter and the receiver have access to accurate and undelayed CSI. It is often difficult to have full CSI in a dynamic environment, since all nodes must continuously track the channel states. To address this issue, optimization based on average channel gains is known as partial CSI. By considering a single relay system with only partial CSI and using CRC to establish correct decoding, [4] concludes that the power allocation in this case is independent of the direct link between source and destination. The solution is accurate for high values of SNR:

$$P_s^{DF} = \frac{1 + \sqrt{1 + C\frac{E[|h_{i'-d}|^2]}{E[|h_{i-i'}|^2]}}}{3 + \sqrt{1 + C\frac{E[|h_{i'-d}|^2]}{E[|h_{i-i'}|^2]}}} P_\Sigma, \quad (5)$$

where C is a positive constant, which depends on the modulation method used. Single relay AF system using mean channel gain CSI is analyzed in [16], where the outage probability is the metric used for optimization. At high SNR, the optimal amplification gain at the relay is:

$$P_s^{AF} = \frac{-1 + \sqrt{1 + 8\frac{E[|h_{i'-d}|^2]}{E[|h_{i-i'}|^2]}}}{4\frac{E[|h_{i-i'}|^2]}{E[|h_{i'-d}|^2]}} P_\Sigma. \quad (6)$$

As a comparison, the solutions from the previous section all assumed full CSI availability. In Fig. 4, we have plotted *DF-Rep(Full CSI)* (4), *AF(Full CSI)* numerical solution [12], *DF-CRC(Partial CSI)* (5) and *AF(Partial CSI)* (6). Note, all these solutions assume full diversity. We can see that the availability of full CSI allows for effective and consistent power allocation as shown by [11]. The partial availability of CSI leads to convergence to a form of equal power allocation as the interuser channel improves. Therefore, from these optimal solutions to relayed networks, we can conclude that the form of power allocation does not depend on the relaying protocol as much as it depends on the diversity order and the CSI available to the transmitters.

IV. Cooperative Network Power Control

A. AF and Repetition Coded DF

Fig. 1 shows a 2 user cooperative network [2] [17], but this can be extended to a M user network. The relaying protocol is to use either AF [3] or more commonly repetition coded DF relaying [6]. The outage or error probability is then minimized assuming perfect CSI availability. The power allocation solution is very similar to the result derived by [10]. The user attempts cooperation if the inter-user channel quality is sufficiently high to guarantee a specific outage probability. For a weak direct link ($| h_{i-d} |^2 < min(| h_{i-i'} |^2, | h_{i'-d} |^2)$), the optimal power allocation for repetition codes is:

$$P_s^{DF} = \frac{2^{2R} - 1}{| h_{i-i'} |^2}, \quad (7)$$

where R is the outrage rate. In [3], a power allocation solution requiring full CSI availability was found for an AF system by minimizing the system bit error rate (BER). The approximate expressions for performance of a M user cooperative system was found by [18] to be:

$$\text{BER}^{AF} = \frac{C(M,k)}{P_r \overline{\gamma}_{i'-d}} \prod_{i=1}^{M} \left(\frac{1}{P_s \overline{\gamma}_{i-i'}} + \frac{1}{P_s \overline{\gamma}_{i-d}}\right), \quad (8)$$

$$C(M,k) = \frac{\prod_{k=1}^{M+1}(2k-1)}{2(M+1)!k^{2(M+1)}} \quad (9)$$

where k is the constant depending on the type of modulation, e.g., for BPSK, $k = 2$. The resulting optimization is non-trivial, but the solutions can be found numerically and demonstrate gains of 5dB at a BER of 10^{-3}.

B. Block Coded DF (Symmetrical)

As one might expect, forward error-correcting codes that improve performance in a point to point network, will have a similar effect in a cooperative network. A DF network utilizing block codes is shown to have a superior performance compared to repetition codes [8]. We first found a closed form expression for block code BER by approximating the complementary error function $\text{erfc}(z) \approx 0.8 \exp(-1.8z^2)$. As in [4], we considered a symmetrical system with M users, each with the same BER expression. Therefore, the system BER is a multiple of the BER of any user. For a n sized block code with error correction ability E, the BER is:

$$\begin{aligned}\text{BER}_{\text{Sys}}^{\text{Sym}} = &\frac{1}{n} \sum_{l=E+1}^{n} \sum_{k=0}^{n-l} \binom{n}{l} \binom{n-l}{k} [\sum_{j=1}^{M-1} \binom{M-1}{j} \\ &\wp^j (1-\wp)^{M-1-j} \frac{l(-1)^k (0.4)^{l+k}}{(1+1.8\overline{\gamma}_{i-d}(l+k)P_s)^{j+1}} \\ &+ (1-\wp)^{M-1} \frac{l(-1)^k (0.4)^{l+k}}{1+1.8\overline{\gamma}_{i-d}(l+k)P_r}].\end{aligned} \quad (10)$$

The chance of cooperation $\wp$ is the chance of no frame errors in the *interuser channel*. This can be obtained using the point to point error rate expression. Under a long term power constraint for each individual user, where power is conserved over N cooperation frames ($P_{\Sigma_i} = 1$), we used Lagrangian methods to optimize the performance. The resulting power allocation solution was found to be:

$$P_s \simeq 1 - \sqrt{\overline{\gamma}_{i-d}} \frac{\sqrt{\overline{\gamma}_{i-i'}^2 + \overline{\gamma}_{i-d}}}{\overline{\gamma}_{i-i'}^2 - \overline{\gamma}_{i-d}}. \quad (11)$$

This was analyzed and optimized for both selfish and unselfish schemes, yielding an intuitive result that power allocation is more effective for networks with unselfish behavior due to the greater cooperation. This is shown in Fig.5, where a (7,4) block code is used for demonstration purposes.

C. Turbo Coded DF (Symmetrical and Asymmetrical)

A similar analysis to Block Codes was extended to any code which can be characterized by an SNR threshold (T), such as Turbo Codes [19]. A distinction between symmetrical and asymmetrical channels had to be made due to the nature of the mathematical expressions for MRC [5]. The symmetrical system frame error rate (FER) for M users is:

$$\begin{aligned}\text{FER}_{\text{Sys}}^{\text{Symm}} = &(1 - e^{-\frac{T}{\overline{\gamma}_{i-i'}\text{P}_r}})^{M-1} \\ &[(1 - e^{-\frac{T}{\overline{\gamma}_{i-d}(\text{P}_r+\text{P}_s)}}) + \frac{(M-1)T\overline{\gamma}_{i-i'}}{2\overline{\gamma}_{i-d}^2 \text{P}_r}].\end{aligned} \quad (12)$$

In order to derive the asymmetrical system FER, we first define a powerset $\mathcal{S}(M, m)$, which contains all the valid

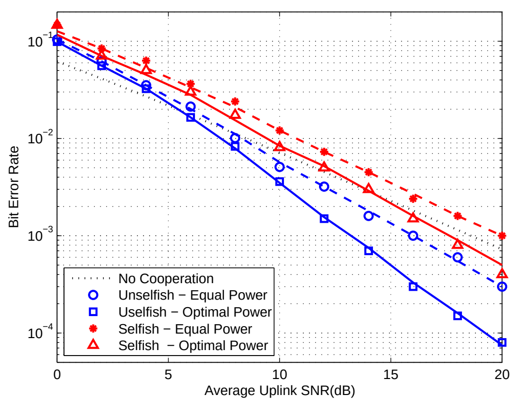

Fig. 5. Block Coded DF: Comparing Power Allocation Benefit in Unselfish and Selfish Cooperation, for $M = 2$ users and 10dB Interuser Average SNR Environment. Symbols indicate simulation results, and lines indicate approximate theoretical expressions.

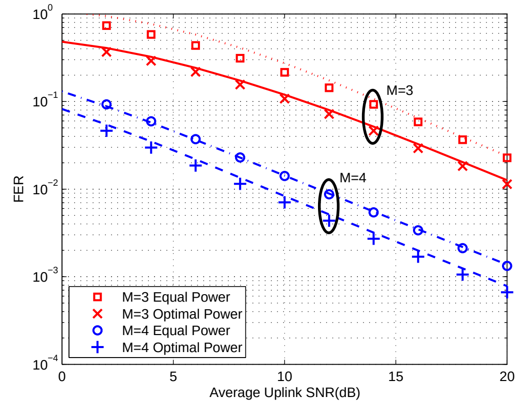

Fig. 6. Turbo Coded Asymmetrical DF: Performance Gain from power allocation with M=3,4 Users. Symbols indicate simulation results, and lines indicate approximate theoretical expressions.

subset combinations for m cooperative partners, of which the subset $\mathcal{U}$ is part of. Hence, $\mathcal{S} \setminus \{\mathcal{U}\}$ is all the remaining subsets excluding $\mathcal{U}$. Therefore, for M users in an asymmetrical system, the FER has the form:

$$\text{FER}_{\text{Sys}}^{\text{Asym}} = \prod_{i'=1, i'\neq i}^{M-1} (1 - \wp_{i'-i})\text{FER}_{\text{Direct}} + \sum_{m=1}^{M-1} \sum_{\mathcal{U}\epsilon\mathcal{S}} \prod_{i'\epsilon\mathcal{U}} \wp_{i-i'} \prod_{i'\epsilon\mathcal{S}\setminus\mathcal{U}} (1 - \wp_{i-i'})\text{FER}_{\text{MRC}}^{\text{Asym}}, \quad (13)$$

where both $\text{FER}_{\text{Direct}}$ and $\wp_{i-i'}$ can be easily obtained using the point to point error rate expression. FER_{MRC} for asymmetric uplink channels is as follows:

$$\text{FER}_{\text{MRC}}^{\text{Asym}} = \sum_{i=0}^{m} \prod_{i'=1, i'\neq i}^{m} \frac{\overline{\gamma}_{i-d}}{\overline{\gamma}_{i-d} - \overline{\gamma}_{i'-d}} (1 - e^{-\frac{T}{\overline{\gamma}_{i-d}}}). \quad (14)$$

With an individual power constraint for each user ($P_{\Sigma_i} = 1$), we first ensured that our metrics and constraints were convex. Then using Lagrangian methods, we arrived at distinctive power allocation solutions for the symmetrical and asymmetrical cases.

$$\text{P}_s^{\text{Symm}} \simeq \frac{1}{M} + \frac{T(2 + 2M^2 - 4M)^{\frac{1}{3}}}{M\overline{\gamma}_{i-i'}\overline{\gamma}_{i-d}^{\frac{1}{3}}}, \quad (15)$$

$$\text{P}_s^{\text{Asym}} = \frac{(\frac{\overline{\gamma}_{i-i'} + \overline{\gamma}_{i-d}}{\overline{\gamma}_{i-i'} + \overline{\gamma}_{i'-d}})^{\frac{1}{3}}}{1 + (\frac{\overline{\gamma}_{i-i'} + \overline{\gamma}_{i-d}}{\overline{\gamma}_{i-i'} + \overline{\gamma}_{i'-d}})^{\frac{1}{3}}}. \quad (16)$$

Due to mathematical difficulties, the asymmetrical case is applicable for $M = 2$ users, and in a $M > 2$ environment, we perform partner selection strategy before employing power allocation. This has been demonstrated to be an effective compromise compared to a benchmark, where we perform optimal power allocation through a brute force solution search. For simulation, a turbo code with generator polynomials $(1, 5/7, 5/7)$ in octal form, a threshold of -4.4dB, and an input frame size of 256 is used. Fig. 6 shows the gain achieved by asymmetrical power allocation. We see that by performing partner selection to simplify the analysis and then performing sub-optimal power allocation, we have improved the FER performance compared to equal power allocation. Fig. 7 shows the performance gain achieved by symmetrical power allocation. The gain achieved by the deterministic solution over equal allocation can be significant in channel conditions which favor adaptive power allocation (i.e., when the interuser channel is not perfect or unusable). All our solutions and performance results are matched with: numerical simulation (symbols), numerical theory and closed form approximated theory (lines).

D. Analysis and Comparison

Our solutions have so far relied on an accurate and averaged CSI feedback in all channels ($\overline{\gamma}$). Currently the receiver averages the perfect channel state estimates, before feeding them back with a delay. Having seen solutions for a variety of cooperation schemes, we are now in a position to compare their performance and power allocation solutions. From Fig. 8, we see that as the interuser channel improves, the higher performance codes require less initial power from the source compared to more trivial codes. This is because the higher performance codes are more likely to guarantee cooperation and subsequently more power is available to the cooperation phase.

V. Conclusion

We first reviewed existing power allocation solutions to what in the main are relay networks, where multiple relays assist a single source in transmission. We concluded that CSI availability and diversity order affected the form of power allocation more so than the relaying protocol or topology. Of the few solutions concerning cooperative

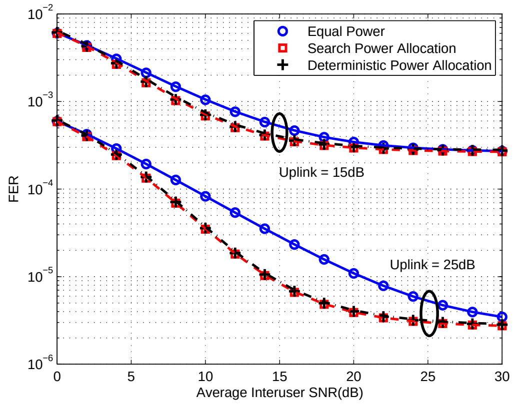

Fig. 7. Turbo Coded Symmetrical DF: Effect of Average Interuser and Uplink Channel SNR of 15 and 25dB on the Power Allocation Factors of $M = 2$ users: symbols indicate simulation results, and lines indicate approximate theoretical expressions.

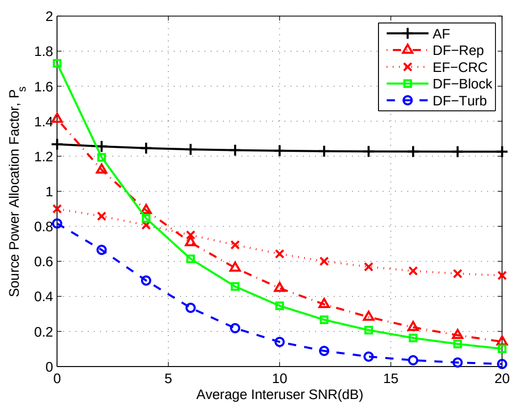

Fig. 8. Comparison of power allocation solutions for AF, Repetition DF, Block DF and Turbo DF

networks, where many users act as relays to each other, the systems considered either use AF, repetition coded DF protocols, or assume perfect interuser channels. Repetition code is generally used in DF protocols, because it yields known tractable expressions. We demonstrate that DF networks using block codes and turbo codes not only out perform a repetition coded system, but can also have error rate expressions whose optimization can lead to power allocation solutions. We introduce power allocation solutions, that rely only on average delayed CSI, to a cooperative network employing such more powerful codes. We compare their performances to existing relay and cooperative networks and showed that our systems outperform existing arrangements and that power allocation further improves system performance. Additionally, we also showed that power allocation is more effective for unselfish than selfish users.

References

[1] J. N. Laneman and G. W. Wornell, "Energy-efficient antenna sharing and relaying for wireless networks," in *Proc. Wireless Communications and Networking Conference*, Sep. 2000, pp. 7–12.

[2] A. Nosratinia, T. E. Hunter, and A. Hedayat, "Cooperative communication in wireless networks," in *IEEE Trans. on Wireless Communications*, vol. 42, no. 10, Oct. 2004, pp. 74–80.

[3] J. Adeane, M. Rodrigues, and I. Wassell, "Optimum power allocation in cooperative networks," in *Proc. Int. Conf. on Telecommunications*, May 2005.

[4] W. Su, A. K. Sadek, and K. J. R. Liu, "Ser performance analysis and optimum power allocation for decode and forward cooperation protocol in wireless networks," in *Proc. Wireless Communications Networking*, Mar. 2005, pp. 984–989.

[5] M. Dohler, A. Gkelias, and A. Aghvami, "Capacity of distributed phy-layer sensor networks," in *IEEE Trans. on Vehicular Technology*, vol. 55, no. 2, Mar. 2006, pp. 622–639.

[6] J. N. Laneman, "Cooperative diversity in wireless networks: algorithms and architectures," MIT, PhD Thesis, 2002.

[7] J. Luo, R. Blum, L. Cimini, L. Greenstein, and A.M.Haimovich, "Decode and forward cooperative diversity with power allocation in wireless networks," in *IEEE Trans. on Inform. Theory*, vol. 50, no. 12, Dec. 2004, pp. 3062–3080.

[8] W. Guo, I. Chatzigeorgiou, I. J. Wassell, and R.Carrasco, "Analysis and adaptive power control for block coded collaborative networks," in *International Wireless Communications and Mobile Computing 2009*, Leipzig, Germany, Jun. 2009.

[9] N. Ahmed, M. Khojastepour, and B. Aazhang, "Outage minimization and optimal power control for the fading relay channel," in *IEEE Inf. Theory Workshop*, Oct. 2004.

[10] D. Gunduz and E. Erkip, "Opportunisti cooperation by dynamic resource allocation," in *IEEE Trans. on Wireless Communications*, vol. 6, Apr. 2007, pp. 1446–1454.

[11] C. T. K. Ng and A. J. Goldsmith, "Capacity gain from transmitter and receiver cooperation," in *IEEE Proc. on Int. Symp. of Inf. Theory*, Sep. 2005, pp. 397–401.

[12] M. O. Hasna and M. S. Alouini, "Optimal power allocation for relayed transmissions over rayleigh fading channels," in *IEEE Trans. Wireless Comms*, Nov. 2004, pp. 1999–2004.

[13] I. Hammerstroem and A. Wittneben, "On the optimal power allocation for nonregenerative ofdm relay links," in *Proc. IEEE Int. Conf. on Comm.*, Jun. 2006, pp. 4463–4468.

[14] Q. Zhang, J. Zhang, C. Shao, Y. Wang, P. Zhang, and R. Hu, "Power allocation for regenerative relay channel with rayleigh fading," in *Proc. Vehicular Technology Conf.*, vol. 2, May 2004.

[15] J. N. Laneman, G. W. Wornell, and D. N. C. Tse, "Cooperative diversity in wireless networks: Efficient protocols and outage behaviour," in *IEEE Trans. on Inform. Theory*, Dec. 2004, pp. 3062–3080.

[16] X. Deng and A. Haimovich, "Power allocation for cooperative relaying in wireless networks," in *IEEE Trans. on Communications*, vol. 50, no. 12, Jul. 2005, pp. 3062–3080.

[17] Y. Cao, B. Vojcic, and M. Souryal, "User cooperative transmision with channel feedback in slow fading channel," in *Proc. Vehicular Technology Conference*, Sep. 2004.

[18] A. Ribeiro, X. Cai, and G. Giannakis, "Symbol error probabilities for general cooperative links," in *36th Asilomar Conference on Signals, Systems and Computers*, vol. 4, no. 3, May 2005, pp. 1264–1273.

[19] I. Chatzigeorgiou, I. J. Wassell, and R. Carrasco, "On the frame error rate of transmission schemes on quasi-static fading channels," in *Proc. Conf. Inf. Sciences and Systems*, Princeton, USA, Mar. 2008, p. 269.