

Cooperative Spatial Reuse with Transmit Beamforming

Chenguang Lu, Frank H.P. Fitzek, and Patrick C.F. Eggers
Department of Electronic Systems
Aalborg University
Niels Jernes Vej 12, DK-9220 Aalborg East, Denmark
E-mail: [cgl,ff,pe]@es.aau.dk

Abstract—A cooperative scheme enabling spatial reuse, namely cooperative spatial reuse (CSR), is proposed as a cooperative extension of the current TDMA-based MAC in wireless networks. In the CSR, a cooperative group is formed by the links that are willing to do spatial reuse. In the group, every cooperating link contributes its time slots for spatial reuse among the cooperating participants. Following the cooperation principle, a link joins the group only if it can benefit. Otherwise, the link will stop doing CSR and switch back to the TDMA-based MAC. In this work, we focus on the transmit beamforming techniques to enable CSR on MISO (Multiple Input Single Output) links. We compared the CSR scheme using zero-forcing (ZF) transmit beamforming, namely ZF-CSR, to the TDMA-based MAC using maximum ratio combining (MRC) transmit beamforming, namely MRC-TDMA. The numerical results of a simulated two 2×1 MISO links scenario show the great potential of CSR to substantially increase the capacity and energy efficiency.

I. INTRODUCTION

In recently years, wireless networks, such as WLAN (wireless local area network), have been increasingly deployed all over the world. In those networks, to reduce the system costs, there is usually no centralized access control. Each link competes for using the channel at a time and operates for its own interests. Current MAC (medium access control) layer protocols like 802.11 MAC [1] are designed to distributedly coordinate the competition in such a way that only one link is allowed to operate at a time in its contention region. It is basically a TDMA-based MAC layer design. When one link obtains the access, the other links in its contention region keep silent during its transmission to avoid collisions. The contention region is usually conservatively specified to keep the interference from outside at a very low level and hence maintain the high link capacity of the active link. However, this design neglects the opportunity of spatial reuse allowing simultaneous transmissions of multiple links.

Spatial reuse has gained a lot of attentions in ad-hoc networks as it has the great potential to increase the network capacity. The current studies on spatial reuse (e.g., [5], [6], [7], [8]) focus on evaluating spatial reuse with respect to the size of the contention region. The analysis is usually based on an assumption of single-rate networks in which all links transmit at a fixed data rate. When one link is transmitting, the other links are allowed during its transmission if the resulted signal-to-interference-and-noise-ratio (SINR) of the current link will not corrupt its ongoing packet reception.

In this work, we propose a cooperative scheme to enable spatial reuse in multi-rate networks — cooperative spatial reuse (CSR) in which every cooperating link contributes its time slots obtained by the TDMA-based MAC to allow spatial reuse among the cooperating participants. Therefore, the CSR is a cooperative extension of the current TDMA-based MAC. Although the capacity of a link is reduced at its own time slots due to the interferences from other links, it is possible for the link to accomplish more traffic during all available time slots as it can get more time slots from others to transmit. Following the cooperation principle [2], every link doing CSR should benefit. Otherwise, it should stop doing it. In this work, we derive the conditions for each link doing CSR to gain more capacity and energy efficiency. The capacity region of CSR is defined. Furthermore, we define the availability of CSR as a measure of its occurrence probability to evaluate how easy to find cooperative partners. This is very important as the efforts should not be wasted in MAC design on something happening rarely.

Lack of interference mitigation capabilities is possibly the reason for current MAC layer designs not considering spatial reuse. However, the wireless networks have been starting evolving to use multiple antenna as the next generation WLAN — MIMO (Multiple Input Multiple Output) WLAN is being standardized [3]. Multiple antenna techniques have been shown the great potential to increase the link capacity by spatial diversity and spatial multiplexing [4]. Meanwhile, it also facilitates spatial reuse by interference cancellation. Thereby, for increasing capacity, multiple antenna techniques can either boost each single link capacity at each time slot or enable spatial reuse to obtain link multiplexing gain. Which scheme is better? In this work, we focus on the transmit beamforming techniques to enable CSR on MISO (Multiple Input Single Output) links. Especially, we take a simulated two-links scenario to show the performance of the CSR with zero-forcing (ZF) transmit beamforming, namely ZF-CSR, compared to the TDMA-based MAC with maximum ratio combining (MRC) transmit beamforming, namely MRC-TDMA. The numerical results show that the ZF-CSR scheme has the great potential to further increase the capacity and energy efficiency of the MRC-TDMA scheme.

The rest of the paper is organized as follows. In Section II, we present the proposed CSR scheme. Section III describes the

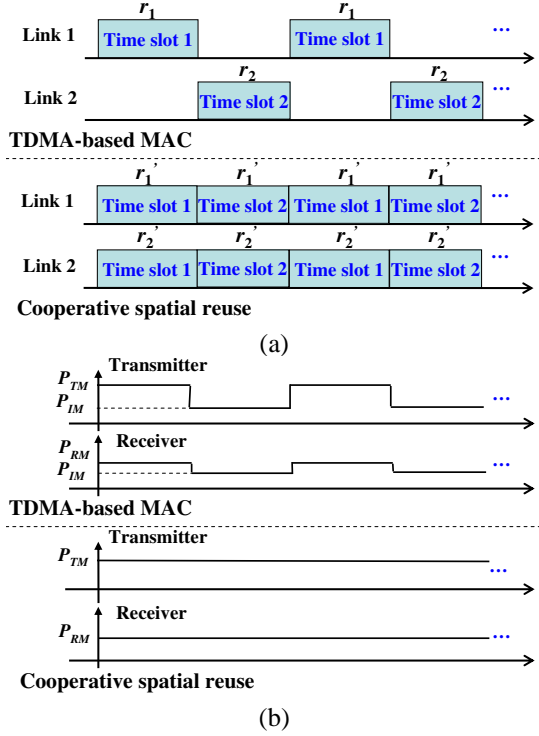


Fig. 1. Illustration of cooperative spatial reuse.

MRC-TDMA and ZF-CSR schemes on MISO links. The numerical results of a two-links scenario are given in Section IV and we conclude the paper in Section V.

II. DESCRIPTION OF THE PROPOSED CSR SCHEME

In TDMA-based MAC layer designs, every link exclusively uses its own time slots. In this sense, every link takes the time slots as its private resource. Doing spatial reuse requires every link to share out its personal time slots for a collective use. Therefore, spatial reuse is to use the time slots cooperatively among links. As a result, every link loses capacity at its personal time slots due to the mutual interferences between links. However, the effective capacity of a link can be increased if the sum capacity obtained from other spatial reused time slots is more than the capacity lost at its personal time slots. As a cooperative scheme following the cooperation principle [2], a spatial reuse scheme should be designed in such a way that every link who contributes its own time slots should obtain enough time slots from the others to guarantee that it gets more capacity.

The basic idea of the proposed CSR scheme is that the cooperating links form a cooperative group sharing all their time slots to multiplex their transmissions. The time slots are obtained by the TDMA-based MAC. A link joins the group only if it can obtain benefits from it, e.g., capacity increase. If no benefit is obtained, it leaves the group and switch back to the TDMA-based MAC. It should be noted that, with the proposed CSR, all other cooperating links should be able to recognize the upcoming time slot for cooperation and be prepared to transmit together with the current link that owns

TABLE I
COMPARISON OF THE TDMA-BASED MAC AND CSR

	TDMA-based MAC	CSR
Effective capacity	$R_i = \frac{T_i}{\sum_{j=1}^k T_j} r_i$	$R_i' = r_i'$
Energy efficiency	$E_i = \frac{P_{XM}T_i + P_{IM}(\sum_{j=1}^k T_j - T_i)}{r_i T_i}$	$E_i' = \frac{P_{XM}}{r_i'}$

the time slot.

As an example, without loss of generality, Fig. 1(a) illustrates a two-links scenario in a round-robin TDMA manner where r_i is the link capacity with the TDMA-based MAC at the time slots owned by the i th link and r_i' is the counterpart with CSR. $r_i' < r_i$ due to the existence of mutual interferences with CSR. Fig. 1(b) shows the power consumption situation of the transmitter and the receiver of link 1. P_{TM} , P_{RM} and P_{IM} are the power consumption of a wireless transceiver in the transmitting mode, receiving mode and idle mode, respectively. When a wireless transceiver is not either transmitting or receiving, it enters into the idle mode to save power. Normally, $P_{TM} > P_{RM} > P_{IM}$.

A. Cooperation conditions

We assume each link has even access probability which is the case in wireless network for the traffic with the same priority. In the following, we derive the cooperation conditions for a link to gain more capacity and energy efficiency.

Without loss of generality, to compare CSR to the TDMA-based MAC, we calculate the mean effective capacity and energy efficiency of each link only within the cooperative group. The energy efficiency is defined as energy consumption per bit. To simplify the analysis, the length of each time slot of a link is assumed equal long and the power consumption parameters (i.e., P_{TM} , P_{RM} and P_{IM}) are assumed the same at each link. The results are summarized in Table I for the k cooperative links scenario. R_i and R_i' are the mean effective capacity of the TDMA-based MAC and CSR, respectively. E_i and E_i' are the mean energy efficiency of the TDMA-based MAC and CSR, respectively. T_i is the length of the time slot of the i th link, $P_{XM} = P_{TM}$ for the transmitter case, and $P_{XM} = P_{RM}$ for the receiver case.

Thereby, comparing to the TDMA-based MAC, there are two conditions for the i th link to benefit from CSR with respect to the effective capacity and energy efficiency, respectively.

Condition I (effective capacity): $R_i' > R_i$ which can be rewritten as

$$R_i' > r_i X_i \quad (1)$$

where $X_i = \frac{T_i}{\sum_{j=1}^k T_j}$.

Condition II (energy efficiency): $E_i' < E_i$ which can be rewritten as

$$R_i' > r_i X_i \frac{1}{X_i + Y(1 - X_i)} \quad (2)$$

where $Y = \frac{P_{IM}}{P_{XM}}$.

For Condition II, there are two cases, the transmitter case where $P_{XM} = P_{TM}$ and the receiver case where $P_{XM} = P_{RM}$. Compares (2) to (1), it is easily seen that Condition II is tougher than Condition I because $\frac{1}{X_i + Y(1 - X_i)} > 1$ with $Y < 1$. When $Y = 0$, Condition II is changed to $R_i' > r_i$ which is impossible due to $R_i' = r_i'$ and $r_i' < r_i$. That means it is impossible for a link to benefit energy efficiency from CSR if the idle mode consumes no power. However, in practice, for instance of 802.11 trceivers, the power consumption of the idle mode is comparable to that of the receiving mode. The trceivers can not shut off all the circuits as they have to be prepared to receive the upcoming packet. Thereby, there is some space for CSR to gain more energy efficiency.

B. CSR capacity region

The CSR capacity region is defined as the region when all cooperative links gain over the TDMA-based MAC. The region is defined as

$$S_{CSR} = \{ (R_1', \dots, R_k') \mid R_1' \in S_1, \dots, R_k' \in S_k \} \quad (3)$$

where

$$S_i = \begin{cases} \{ R_i' \mid R_i' > R_i \}, & \text{on Condition I} \\ \{ R_i' \mid E_i' < E_i \}, & \text{on Condition II} \end{cases} \quad (4)$$

Each link chooses Condition I or Condition II based on its own situation. If energy efficiency is its main concern (e.g., in the case of battery-powered devices), it should choose Condition II. Otherwise, it should choose Condition I.

C. CSR availability

Another important aspect to evaluate the usability of a CSR scheme is on how easy to form a cooperative group. Links are willing to try CSR only if it is not difficult to find cooperative partners around. Therefore, we define the CSR availability as the probability falling into the CSR region

$$A_{CSR} = P_r[(R_1', R_2', \dots, R_k') \in S_{CSR}] \quad (5)$$

If the availability is low, it is not worthwhile using CSR as the partner finding process will waste a lot of capacity.

III. CSR WITH TRANSMIT BEAMFORMING ON MISO LINKS

A. Transmit beamforming on MISO links

In this work, the focus is on the transmit beamforming techniques on MISO links to investigate the potential of CSR. It also reflects a downlink scenario with multiple-antenna access points and single-antenna terminals. Fig. 2 shows k $n \times 1$ MISO links including a beamforming transmitter with n antennas and k single-antenna receivers where the 1st receiver is the intended receiver. Therefore, the received signal at the i th receiver is expressed as

$$r_i(t) = (\mathbf{h}_i)^T \mathbf{w} s(t) + n_i(t) \quad (6)$$

where $(\cdot)^T$ denotes the transpose of a vector, $\mathbf{h}_i = [h_{1i} \ h_{2i} \ \dots \ h_{ni}]^T$ is the channel vector of the i th MISO

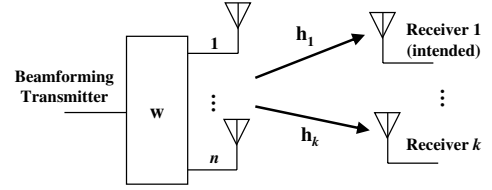


Fig. 2. MISO links with transmit beamforming

TABLE II
WEIGHT VECTOR OF MRC-TDMA AND ZF-CSR

	MRC-TDMA	ZF-CSR
Weight vector	$\mathbf{w}_{MRC} = \frac{(\mathbf{h}_1)^*}{\ (\mathbf{h}_1)^*\ }$	$\mathbf{w}_{ZF} = \frac{\mathbf{H}^+ \mathbf{I}_{k \times 1}}{\ \mathbf{H}^+ \mathbf{I}_{k \times 1}\ }$

link, $\mathbf{w} = [w_1 \ w_2 \ \dots \ w_n]^T$ is the weight vector, $s(t)$ is the transmitted signal, and $n_i(t)$ is the noise at the i th receiver.

With the TDMA-based MAC, the capacity can be enhanced by focusing the beam to the intended receiver to achieve array gain and diversity gain. The beamforming technique can also be used to cancel the mutual interferences between cooperating links to enable CSR. In the following, we will compare two transmit beamforming schemes with the TDMA-based MAC and CSR, respectively, namely MRC-TDMA and ZF-CSR.

B. MRC-TDMA versus ZF-CSR

The MRC-TDMA scheme uses the TDMA-based MAC and each beamforming transmitter applies MRC weight vector to maximize the signal-to-noise-ratio (SNR) at the intended receiver and thus maximize the capacity of the MISO link. In the ZF-CSR scheme, the weight vector of each cooperating transmitter is set in such a way that the received signal at the receivers of other cooperating links are canceled (forced to be zero). Therefore, the cooperating links can transmit simultaneously without the mutual interferences.

Table II gives the weight vector setting of the two schemes. For a fair comparison, the weight vectors are normalized. \mathbf{h}_1 denotes the channel vector of the desired link, $(\cdot)^*$ denotes the conjugate of a vector, $\|\cdot\|$ denotes the Euclidean norm of a vector, $\mathbf{H} = [\mathbf{h}_1 \ \mathbf{h}_2 \ \dots \ \mathbf{h}_k]^T$ is the channel matrix of the cooperating links, $(\cdot)^+$ denotes the pseudoinverse of a matrix, and $\mathbf{I}_{k \times 1}$ denotes the first column of a $k \times k$ identity matrix.

As the MRC-TDMA scheme maximizes the SNR at the intended receiver, the SNR of the ZF-CSR scheme is lower for canceling the interferences. The reduced SNR with the ZF-CSR scheme gives the lower data rate than the MRC-TDMA scheme. In this work, we will calculate the link capacity of the two schemes from the information-theoretical point of view. According to the information theory, the channel capacity of the beamforming MISO link on a AWGN channel is expressed as

$$C = \log_2(1 + SNR) \quad (\text{bits/s/Hz}) \quad (7)$$

where SNR is the SNR at the intended receiver.

IV. NUMERICAL EXAMPLES

In the following, we will take a simulated scenario of two 2×1 MISO links to illustrate the potential of the ZF-CSR scheme compared to the MRC-TDMA scheme. Especially, we will show the CSR availability, average capacity gain, and average energy efficiency saving. Assume the fading channel on each branch is the i.i.d complex Gaussian channel and the noise is AWGN. The perfect channel knowledge is assumed available at the transmitters. Furthermore, we assume the even access probability of each link as discussed in Section II. The time slot length of each link, T_i in Table I, is fixed and $T_i \propto 1/r_i$ where r_i is the data rate of the i th link with the MRC-TDMA scheme. This reflects the scenario with the fixed packet length at each time slot of each link. The power consumption parameters are set such that $P_{TM} = 2 \text{ Watt}$, $P_{RM} = 0.95 \text{ Watt}$ and $P_{IM} = 0.85 \text{ Watt}$. In the simulation, 1,000,000 channel realizations are simulated on each link to obtain the capacity statistics. The mean SNR of each branch on each link is from 10 to 30 dB, which are the practical values for dense deployed networks. The performance evaluation is based on the channel capacity using (7) from the information-theoretical point of view. The channel capacity is used as the data rate of each link. The results are useful as the advanced coding techniques approach the channel capacity. In practice, the gradient of the actual rate adaptation curve (data rate versus SNR) is even less than that of the channel capacity curve. In this case, the actual performance will be even better than the simulation results.

A. CSR availability

Fig. 3(a) shows the CSR availability versus the mean SNR per branch (SNR_b) on the two links when both links satisfy Condition I. Generally, the availability decreases as the SNR of either link decreases. The decreasing rate of the availability over the SNR increases as the SNR difference of the two links increase. For the whole SNR region, the availability is fairly high from about 0.6 up to about 0.9. It means that it is fairly easy for a link to find a cooperative partner to both achieve more capacity.

Fig. 3(b) and Fig. 3(c) show the availability when both links satisfy Condition II. Fig. 3(b) shows the receiver case where $P_{XM} = P_{RM}$ in (2) for both links while Fig. 3(c) shows the transmitter case where $P_{XM} = P_{TM}$. As expected, the availability is lower than the Condition I case as Condition II is tougher. Furthermore, the availability is reduced less in the receiver case than the transmitter case as $P_{RM} < P_{TM}$. The availability range for the receiver case is still fairly high from about 0.55 up to about 0.9 while it is reduced to the range from about 0.35 to about 0.75 for the transmitter case. The availability reduction of the receiver case is small as P_{RM} is just slightly higher than P_{IM} . Therefore, it is fairly easy for two links to form a cooperative group to make both receivers more energy efficient. However, it is much more difficult to achieve more energy efficiency at both transmitters.

B. Capacity gain

In the following, we will show the capacity gain when a cooperative group is successfully formed. Fig. 4(a) and Fig. 4(b) show the average ZF-CSR capacity compared to that of the MRC-TDMA scheme on link 1 and link 2, respectively, when both links satisfy Condition I. As expected, the average capacity on link 1 and link 2 are symmetric. The link with higher SNR will obtain more gain. For example, when SNR_b on link 1 is about 30 dB and SNR_b on link 2 is about 10 dB, link 1 can obtain averagely over 3 times the capacity of the MRC-TDMA scheme while link 2 only achieve less than 1.4 times. It is due to the difference of the time slot length of the two links. As the packet length is fixed for each time slot, the higher SNR link has a shorter time slot than the lower SNR link as the higher SNR offers the higher data rate. As a result, the higher SNR link can get a longer time slot from the lower SNR link to compensate the capacity loss at its own time slot while the lower SNR link get a shorter time slot from the higher SNR link. For the whole SNR region, each link achieves from about 1.4 up to about 3 times the capacity of the MRC-TDMA scheme. Fig. 4(c) shows the total average capacity gain of both links. The whole cooperative group can obtain the significantly increased capacity from about 1.7 to about 2.1 times the capacity before.

C. Energy efficiency saving

Fig. 5 shows the average energy efficiency saving when both links satisfy Condition II for the receiver case. The energy efficiency saving measures how much percentage energy is saved per bit than that of the MRC-TDMA scheme. Fig. 5(a) and Fig. 5(b) show the results of link 1 and link 2, respectively. Similar to the capacity gain, the average energy efficiency savings at the receivers of link 1 and link 2 are symmetric. The higher SNR link saves more energy per bit as it has the higher capacity gain as shown in Fig. 4. For example, when SNR_b on link 1 is about 30 dB and SNR_b on link 2 is about 10 dB, link 1 can save averagely over 60% energy per bit than before while link 2 only saves less than 20%. For the whole SNR region, the average energy efficiency saving of each link is significant from about 20% up to about 60% than before. Fig. 5(c) shows the total energy efficiency saving of both links. The whole cooperative group can save from about 35% to about 39% energy per bit than before.

V. CONCLUSIONS

The CSR scheme performs as a cooperative extension of the current TDMA-based MAC to enable spatial reuse in wireless networks. We derive the cooperation conditions for a link to do CSR to gain more capacity and energy efficiency. To further evaluate the usability of CSR, the CSR availability is defined to measure how difficult for links to form a cooperative group. We investigate the potential of CSR with a two 2×1 MISO beamforming links scenario. The numerical results show the significant gain of the ZF-CSR scheme than the MRC-TDMA scheme. In dense deployed networks that have high SNR on each link, the availability results show that it is fairly easy

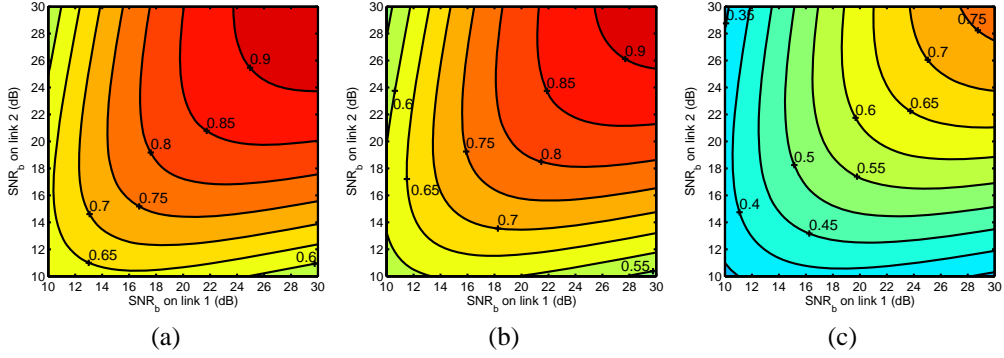


Fig. 3. CSR availability (a) when both links satisfy Condition I, (b) when both links satisfy Condition II for the receiver case where $P_{XM} = P_{RM}$, and (c) when both links satisfy Condition II for the transmitter case where $P_{XM} = P_{TM}$. SNR_b denotes the mean SNR per branch.

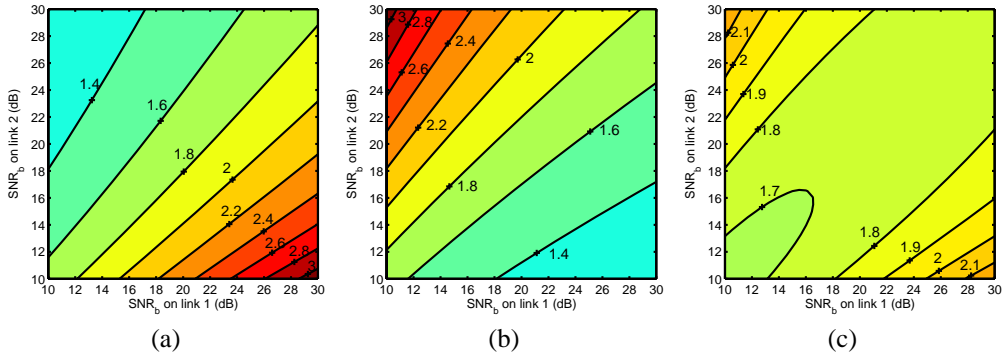


Fig. 4. Average CSR capacity compared to that of the TDMA-based scheme when both links satisfy Condition I on (a) link 1, (b) link 2, and (c) both links.

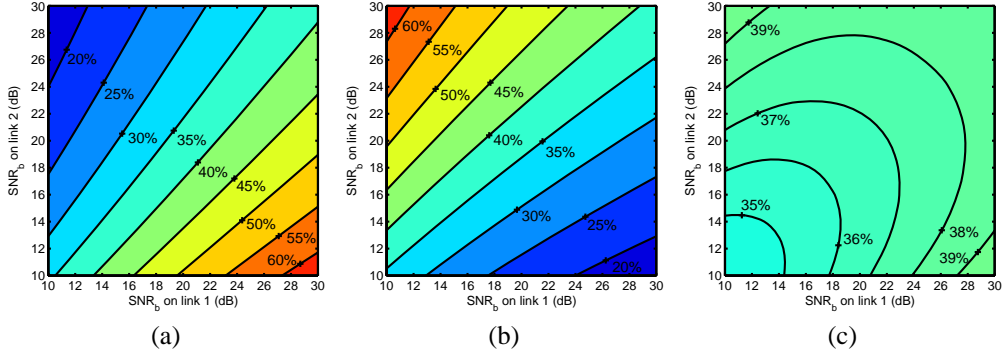


Fig. 5. Average CSR energy efficiency saving when both links satisfy Condition II for the receiver case on (a) link 1, (b) link 2, and (c) both links.

for two links to form a cooperative group to both gain more capacity and more energy efficiency at the receivers. The average capacity of each link is from 1.4 to 3 times that of the MRC-TDMA scheme while the average capacity of the whole group is from 1.7 to 2.1 times that before. The receiver of each link can save averagely from 20% to 60% energy per bit while the both receivers save from 35% to 39%. Therefore, the CSR scheme has the great potential to further increase the capacity and energy efficiency in MISO wireless networks using transmit beamforming.

REFERENCES

- [1] IEEE-802.11, "Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications," *ANSI/IEEE Std 802.11, 1999 Edition (R2003)*, pp. i-513, 2003.
- [2] F.H.P Fitzek and M.Katz, editors, *Cooperation in Wireless Networks: Principles and Applications — Real Egoistic Behavior is to Cooperate!*, ISBN 1-4020-4710-X. Springer, Apr. 2006.
- [3] S.A. Mujtaba, et al., "TGN sync proposal technical specification," IEEE 802.11-04/0889r7, Jul. 2005.
- [4] H. Boche, A. Bourdoux, J.R. Fonollosa, T. Kaiser; A. Molisch, and W. Utschick, "Smart antennas: state of the art," *IEEE Veh. Tech. Mag.*, vol.1, no.1, pp. 8-17, Mar. 2006.
- [5] F. Ye and B. Sikdar, "Distance-aware virtual carrier sensing for improved spatial reuse in wireless networks," in *Proc. IEEE GLOBECOM 2004*, vol.6, pp. 3793-3797, Nov. 2004.
- [6] F. Ye, S. Yi, and B. Sikdar, "Improving spatial reuse of IEEE 802.11 based ad hoc networks," in *Proc. IEEE GLOBECOM 2003*, vol.2, pp. 1013-1017, Dec. 2003.
- [7] K. Xu, M. Gerla, and S. Bae, "How effective is the IEEE 802.11 RTS/CTS handshake in ad hoc networks," in *Proc. IEEE GLOBECOM 2002*, vol. 1, pp. 72-76, Nov. 2002.
- [8] X. Guo; S. Roy; W.S. Conner, "Spatial reuse in wireless ad-hoc networks," in *Proc. IEEE VTC 2003-Fall*, vol. 3, pp. 1437-1442, Oct. 2003.