Cooperative Spatial Reuse with Transmit Beamforming in Multi-rate Wireless Networks

Lu, Chenguang; Fitzek, Frank; Eggers, Patrick Claus F.

Published in:
Journal of Communications

DOI (link to publication from Publisher):
10.4304/jcm.4.1.26-33

Publication date:
2009

Document Version
Publisher's PDF, also known as Version of record

Cooperative Spatial Reuse with Transmit Beamforming in Multi-rate Wireless Networks

Chenguang Lu
Ericsson Reasearch, Stockholm, Sweden
E-mail: chenguang.lu@ericsson.com

Frank H. P. Fitzek, Patrick C. F. Eggers
Department of Electronic Systems, Aalborg University, Aalborg, Denmark
E-mail: {ff,pe}@es.aau.dk

***Abstract*—We present a cooperative spatial reuse (CSR) scheme as a cooperative extension of the current TDMA-based MAC to enable spatial reuse in multi-rate wireless networks. We model spatial reuse as a cooperation problem on utilizing the time slots obtained from the TDMA-based MAC. In CSR, there are two operation modes. One is TDMA mode while the other is spatial reuse mode in which links transmit simultaneously. Links contribute their own time slots to form a cooperative group to do spatial reuse. Each link joins the group only if it can benefit in capacity or energy efficiency. Otherwise, the link will leave spatial reuse mode and switch back to TDMA. In this work, we focus on the transmit beamforming techniques to enable CSR by interference cancellation on MISO (Multiple Input Single Output) links. We compare 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 recent years, WLANs (wireless local area networks) have been explosively deployed all over the world for its high data rate, low costs and ease for installation. WLAN technologies have been the most popular broadband wireless access technologies used in home, corporate and other public networks. The built-in multi-rate capability provides the highest data rate availble to users according to their perceived signal to noise ratio (SNR). To reduce the overall system costs, WLAN MAC protocols (i.e. 802.11 MAC [1]) adopts distributed access control. Each link competes for using the frequency channel at a time, while the competition is distributedly coordinated such that only one link is allowed to operate at a time in its contention region. Therefore, 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. To cover a large area, reusing the same frequency channel in different cells is inevitable due to the limited number of non-overlapped frequency channels available (e.g. only 3 non-overlapped frequency channels available in the most popular 2.4 GHz band.) [3]. It often happens in densely deployed area that the access points using the same channel are within the contention region of each other. Therefore, the downlink capacity of those cells would be limited to one cell capacity, as those cells share the channel in a TDMA manner.

Addressing this problem, in our previous conference paper [2], we proposed a scheme named cooperative spatial reuse (CSR) to enable spatial reuse opportunistically. This paper is an extended paper to give a more complete picture of the CSR scheme with extended explanations and discussions. In CSR, we model spatial reuse as a cooperation problem between nodes on top of the current TDMA-based MAC. Every cooperating link contributes its time slots obtained from the TDMA-based MAC to allow spatial reuse among the cooperating participants. Although one link loses some capacity at its own time slots due to the interferences from the other links, it is possible for the link to achieve more capacity during all available time slots, as it can get more time slots from others to transmit. Following the cooperation principle [4], every link doing CSR should benefit. Therefore, in CSR, the links that can not benifit from spatial reuse will switch back to the TDMA-based MAC. 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 to measure how difficult for links to find cooperative partners to benefit. This is very important as links could lose some capacity during the partner finding process.

Lack of interference mitigation capabilities is possibly the reason for current MAC layer designs not to consider spatial reuse. However, wireless networks have been starting evolving to use multiple antenna, as the next generation WLAN — MIMO (Multiple Input Multiple

This paper is based on “Cooperative Spatial Reuse with Transmit Beamforming,” by C. Lu, F. H. P. Fitzek, and P. C. F. Eggers, which appeared in the Proceedings of IEEE 66th Vehicular Technology Conference, Baltimore, USA, September 2007.

Output) WLAN is being standardized [5]. Multiple antenna techniques have been shown the great potentials to increase the link capacity by spatial diversity and spatial multiplexing [6]. 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. It reflects the most relevant downlink scenario where the access points have multiple antnenas and the terminals have only single antenna. 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 give a brief overview of the related works. In Section III, we present the proposed CSR scheme. Section IV describes the MRC-TDMA and ZF-CSR schemes on MISO links. The numerical results of a two-links scenario are given in Section V and we conclude the paper in Section VI.

II. Related works

Spatial reuse has gained a lot of attentions in ad-hoc networks as it has the great potential to increase the network capacity — the sum capacity of the whole network, whereas our CSR scheme considers to increase the capacity of each individual link. The basic assumption is that ad-hoc networks are fixed rate networks in which every link transmit at a fixed data rate. The related studies on ad-hoc networks are all based on the capature effects that one receiver can still capture (or correctly decode) the desired packet with the interferences as long as the perceived signal-to-interference-and-noise-ratio (SINR) is higher than the required SINR for the certain data rate of the ad-hoc network.

Some studies (e.g., [7]–[10]) focus on evaluating spatial reuse with respect to the size of the contention region. More links can transmit simultaneously by shrinking the contention region, while keeping the SINR of each link to be able to capture its desired packets. In practice, it can be done by tuning the carrier sense threhold. Carefully choosing the optimum threhold can increase the network capacity dramatically than the current conservative setting.

Some studies (e.g., [11]–[14]) focus on using directional antenna to facilitate spatial reuse. Directional antenna can concentrate their antenna pattern to the related direction of the desired signal to increase the SINR of each link. The increased SINR can increase the capture probability of links. Therefore, more links can transmit

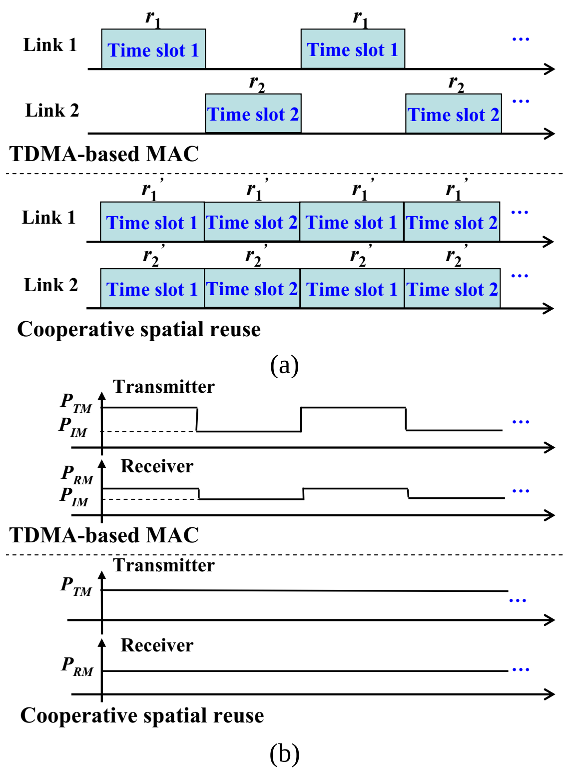


Fig. 1. Illustration of cooperative spatial reuse of a two-links example.

simultaneously with the successful capture of their desired packets. It would further significantly increase the network capacity, especially in outdoor environments where line of sight (LOS) is available.

III. Description of the proposed CSR scheme

In the current TDMA-based MAC layer design, 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 some capacity at its personal time slots due to the mutual interferences between links. However, the effective capacity of one link can be increased if the sum capacity obtained from other spatial reused time slots is more than the capacity loss at its personal time slots. As a cooperative scheme following the cooperation principle [4], a spatial reuse scheme should be designed in such a way that every link that 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. One 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. Therefore, CSR is a cooperative extension of the current TDMA-based MAC and enable spatial reuse

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	$E_i = \frac{P_{XM} T_i + P_{IM} (\sum_{j=1}^{k} T_j - T_i)}{r_i T_i}$	$E_i{}' = \frac{P_{XM}}{r_i{}'}$

opportunistically. It has two modes, TDMA and spatial reuse, to utilize the time slots. It switches between the two modes and make the best of them. 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 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 of the ith link with TDMA-based MAC and $r_i{}'$ is the counterpart with spatial reuse mode of CSR. $r_i{}' < r_i$ due to the existence of mutual interferences in spatial reuse mode. 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 one wireless tranceiver in the transmitting mode, receiving mode and idle mode, respectively. When one wireless tranceiver 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 that each link has even access probability which is the case in WLANs for the traffic with the same priority. In the following, we derive the cooperation conditions for one 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. In CSR, we only show them in the spatial reuse mode as the TDMA mode is the same as the TDMA-based MAC. To simplify the analysis, the time slot length of one link is assumed fixed while the power consumption parameters (i.e., P_{TM}, P_{RM} and P_{IM}) are assumed the same for all links. The results are summarized in Table I for the k 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 ith link, $P_{XM} = P_{TM}$ for the transmitter case, and $P_{XM} = P_{RM}$ for the receiver case.

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

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

$$R_i{}' > r_i X_i \tag{1}$$

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

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

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 is designed ideally such that it consumes no power. However, in practice, for instance of 802.11 tranceivers, the power consumption of the idle mode is comparable to that of the receiving mode. The tranceivers can not shut off all the circuits as they have to be prepared to receive the upcoming packet. Therefore, there is some space for CSR to gain more energy efficiency, as the energy is wasted in the TDMA based MAC by transmitting and receiving nothing in the idle time slots.

B. CSR capacity region

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

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

where

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

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.

Fig. 2 illustrates the CSR capacity region for the case of two links. The line DE represents the achievable capacity with the TDMA-based MAC during the two time slots with all possible time sharing ratio, i.e., T_1/T_2 in this case. Point D and E are the extreme cases when one of two links occupies both time slots, i.e., $T_1/T_2 = 0 \; or \; \infty$. In the other words, there is only one active link at point D and E. In these two extreme cases, the active link achieves its link capacity, r_1 or r_2. In other points on the line, the effective capacity of two links are reduced due to the time sharing. As an example, point A is an operational point for a given time sharing ratio specified by the TDMA-based MAC used. At point A, R_1 and R_2 represent the

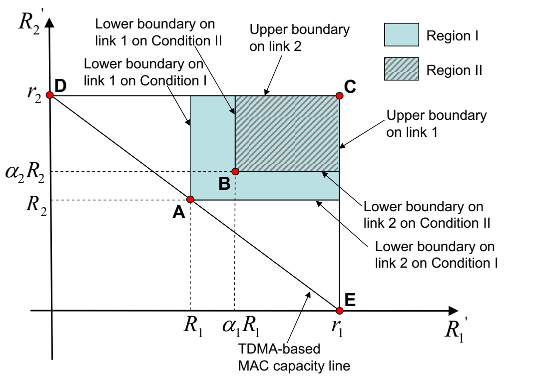


Fig. 2. Illustration of the CSR capacity region of a two-links example

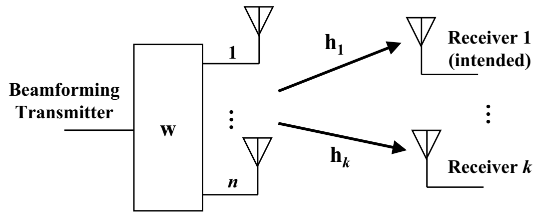


Fig. 3. MISO links with transmit beamforming

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

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

effective capacity of the two links. Therefore, for point A, Region I shows the capacity region when both links satisfy Condition I, while Region II shows the capacity region when both links satisfy Condition II where $\alpha_i = \frac{1}{X_i+Y(1-X_i)}$ following (2). Region II is a subset of Region I as Condition II is tougher than Condition I. To be noted, point C can be approached, for an instance, when two links are separated at infinity distance. Moreover, for the beamforming case, it can also achieved when the channels are well separated such that the mutual interferences can be completely nulled by the beams which are also optimal for the reception of the desired signals on both links in the interference-free case.

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

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

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

IV. 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 the most relevant downlink scenario with multiple-antenna access points and single-antenna terminals. Fig. 3 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 ith receiver is expressed as

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

where $(\cdot)^T$ denotes the transpose of a vector, $\mathbf{h}_i = [h_{1i}\ h_{2i}\ ...\ h_{ni}]^T$ is the channel vector of the ith MISO link, $\mathbf{w} = [w_1\ w_2\ ...\ w_n]^T$ is the weight vector, $s(t)$ is the transmitted signal, and $n_i(t)$ is the noise at the ith 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, $\mathbf{H} = [\mathbf{h}_1\ \mathbf{h}_2\ ...\ \mathbf{h}_k]^T$ 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.

1) SNR comparison: As the MRC transmit beamforming maximizes the SNR at the intended receiver, the SNR of ZF transmit beamforming is lower for canceling the interferences. In principle, on the i.i.d. (independent, identically distributed) complex Gaussian fading channel, the M-branch (M-antenna) MRC beamforming can provide M-fold of diversity order. For the M-branch ZF beamforming canceling the interferences at L receivers, the diversity order is reduced to $M - L$ [15]. As an example, we compare the SNR at the intended receiver of the two schemes in a scenario of two 2×1 MISO

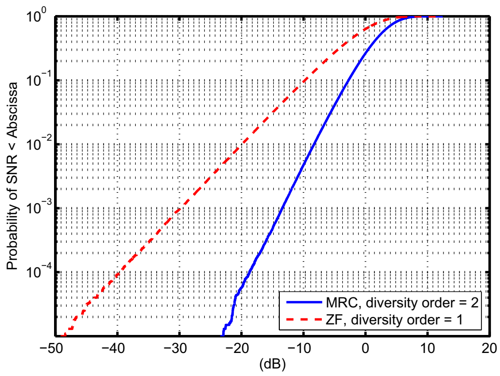


Fig. 4. CDF of the SNR of the ZF beamforming and the MRC beamforming.

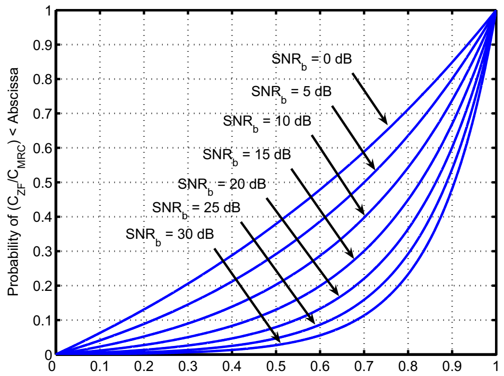


Fig. 5. CDF of the channel capacity ratio between ZF-CSR and MRC-TDMA, (C_{ZF}/C_{MRC}), on the desired link. SNR_b denotes the mean SNR per branch.

links. The MRC-TDMA scheme uses the 2-branch MRC beamforming while the ZF-CSR scheme uses the 2-branch ZF beamforming that cancels one interference. Fig. 4 shows the CDF (cumulative distribution function) of the SNR at the intended receiver over 1,000,000 channel realizations. In the simulation, the i.i.d. complex Gaussian fading channel is assumed and the mean SNR per branch is 0 dB. It shows that MRC beamforming achieves diversity order of 2 while ZF beamforming achieves diversity order of 1.

2) Link capacity comparison: The reduced SNR at the intended receiver with the ZF-CSR scheme gives the lower data rate on the desired link than the MRC-TDMA scheme. In this work, we compare the link capacity on the desired link of the two schemes from the information-theoretical point of view. According to information theory [16], the channel capacity of the beamforming MISO link on a AWGN (additive white Gaussian noise) channel is expressed as

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

where SNR is the SNR at the intended receiver.

For the same two-links example shown in Fig. 4, Fig. 5 shows the CDF of the channel capacity ratio between the ZF-CSR scheme and the MRC-TDMA scheme. It shows the relative channel capacity loss on the desired link with the ZF-CSR scheme. The probability that the channel capacity ratio is less than a given value increases as the SNR per branch decreases. Therefore, the higher SNR gives the less loss in the channel capacity for using the ZF beamforming. For example, the ZF beamforming can achieve over 70% channel capacity of the MRC beamforming in about 90% cases when the SNR per branch is 30 dB. However, when the SNR per branch is 0 dB, only about 40% cases give over 70% channel capacity of the MRC beamforming. To fulfill the cooperation conditions of CSR, the low capacity loss means that the link needs less time slots from the other links to compensate its capacity loss. Therefore, the higher SNR should give the higher CSR availability.

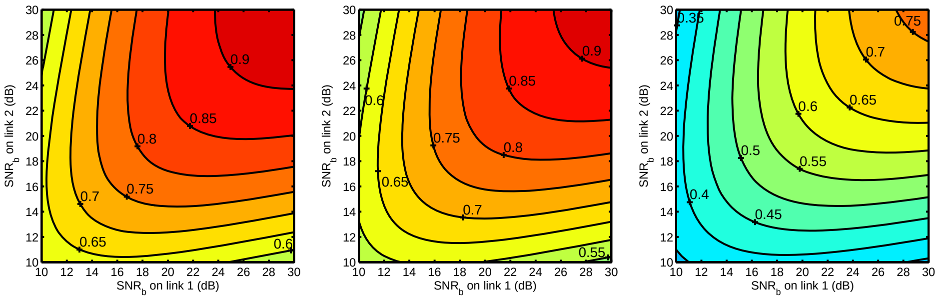
Even though the above analysis is based on the channel capacity, it is useful as the advanced coding techniques approach the channel capacity. In practice, the gradient of the actual rate adaptation curve (data rate versus SNR) is even less than that of the channel capacity versus SNR curve. In this case, the actual performance will be even better than the results above.

V. Numerical Results

In the following, we will take a simulated scenario of two 2×1 MISO links to show the potential of the ZF-CSR scheme in comparison 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 III. 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 ith link with the MRC-TDMA scheme. This reflects the scenario with the fixed packet length at each time slot of each link, which is usually the case of the current WLAN fairness scenario that follows max-min fairness. The power consumption parameters are set such that $P_{TM} = 2\ Watt$, $P_{RM} = 0.95\ Watt$ and $P_{IM} = 0.85\ Watt$, which are the typical values of WLAN transceivers. 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 densely 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.

A. CSR availability

Fig. 6(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. This is because the lower SNR gives more relative capacity loss for ZF-CSR. The decreasing rate of the availability over the SNR increases



(a) (b) (c)

Fig. 6. 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.

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. 6(b) and Fig. 6(c) show the availability when both links satisfy Condition II. Fig. 6(b) shows the receiver case where $P_{XM} = P_{RM}$ in (2) for both links while Fig. 6(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

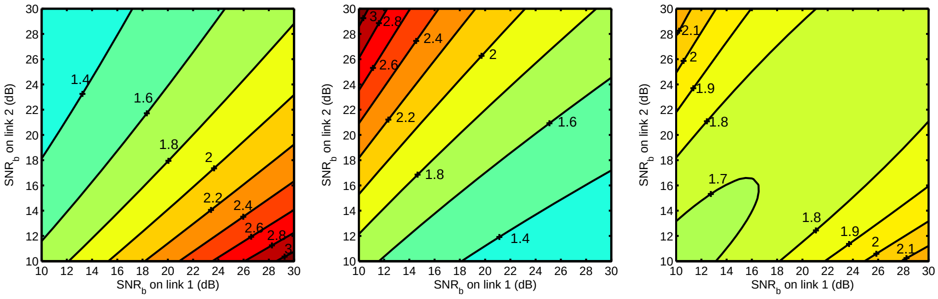
From above discussions, it is not difficult for one link to find a cooperative partner to both obtain more capacity. We will show the capacity gain when both links gain more capacity. Fig. 7(a) and Fig. 7(b) show the average ZF-CSR capacity compared to that of the MRC-TDMA scheme on link 1 and link 2, 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. 7(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 of MRC-TDMA.

C. Energy efficiency saving

Fig. 8 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. 8(a) and Fig. 8(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. 7. 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. 8(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 MRC-TDMA.

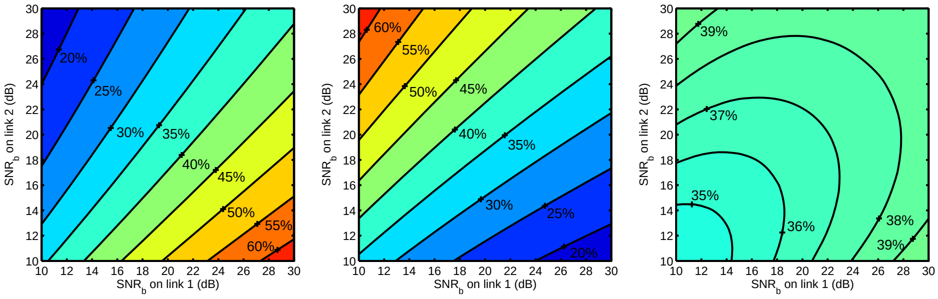
VI. Conclusions and Discussions

The CSR scheme performs as a cooperative extension of the current TDMA-based MAC to enable spatial reuse in multi-rate wireless networks like WLANs. We derive the cooperation conditions for one 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 densely deployed networks that have high SNR on each link, the availability results show that it is fairly easy 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



(a) (b) (c)

Fig. 7. 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.



(a) (b) (c)

Fig. 8. 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.

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 both receivers save from 35% to 39%.

The great performance improvement of CSR with transmit beamforming mainly comes from the interference cancellation capability provided by multiple antenna techniques. From the propagation point of view, as long as the signals of different links are well separated in spatial domain with respect to their spatial signatures, it brings the high efficiency of interference cancellation. Doing interference cancellation will not reduce much capacity of the desired link. In this case, the network capacity will be dramatically improved over the TDMA case by spatial reuse allowing links transmit simultaneously. However, when the signals have close spatial signatures, the links should not transmit simultaneously and instead should perform the TDMA transmission as interference cancellation efficiency is low. It indicates that to maximize the network capacity the network should be divided into groups in which the links are well separated and therefore do spatial reuse, while the transmissions of different groups should follow TDMA. This could be a very interesting future work from the network point of view.

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] C. Lu, F.H.P. Fitzek, and P.C.F. Eggers, “Cooperative Spatial Reuse with Transmit Beamforming,” *in Proc. IEEE VTC 2007 Fall*, pp. 1623-1627, October 2007.

[3] T.S. Rappaport, *Wireless Communications: Principles and Practice*, ISBN 0-13-042232-0, Prentice Hall, 2001.

[4] 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.

[5] S.A. Mujtaba, et al., “TGn sync proposal technical specification,” IEEE 802.11-04/0889r7, Jul. 2005.

[6] 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.

[7] 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.

[8] 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.

[9] 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.

[10] X. Guo, S. Roy, and W.S. Conner, “Spatial reuse in wireless adhoc networks,” *in Proc. IEEE VTC 2003-Fall*, vol. 3, pp. 1437-1442, Oct. 2003.

[11] Y. Ko, V. Shankarkumar, and N. H. Vaidya, “Medium access control protocols using directional antennas in ad hoc networks,” *in Proc. IEEE INFOCOM 2000*, March 2000, vol. 1.

[12] A. Nasipuri, S. Ye, J. You, and R. Hiromoto, “A MAC protocol for mobile ad hoc networks using directional antennas,” *in Proce. IEEE WCNC 2000*, September 2000, vol. 3, pp. 12141219.

[13] R. Roy Choudhury, X. Yang, N. H. Vaidya, and R. Ramanathan, “Using directional antennas for medium access control in ad hoc networks,” *in Proc. ACM MOBICOM 2002*, September 2002.

[14] M. Takai, J. Martin, R. Bagrodia, and A. Ren, “Directional virtual carrier sensing for directional antennas in mobile ad hoc networks,” *in Proc. ACM MobiHoc 2002*, June 2002, pp. 3946.

[15] R. G. Vaughan and J. B. Andersen, *Channels, Propagation and Antennas for Mobile Communications*, ISBN 0852960840, IEE: Institution of Electrical Engineers, 2003.

[16] T.M. Cover and J.A. Thomas, *Elements of Information Theory*, ISBN 0-471-24195-4, New York: Wiley, 2006.

Chenguang Lu received his B.Sc. degree in electrical engineering from Shandong University of Technology, China, in 2000, his M.Sc. degree in electrical engineering from Chalmers University of Technology, Sweden, in 2006, and his Ph.D. degree in electrical engineering from Aalborg University, Denmark, in 2008. He is currently with Ericsson Research as a research engineer.

Frank H. P. Fitzek is an Associate Professor in the department of Electronic Systems, University of Aalborg, Denmark heading the Future Vision group. He received his diploma (Dipl.-Ing.) degree in electrical engineering from the University of Technology - Rheinisch-Westfälische Technische Hochschule (RWTH) - Aachen, Germany, in 1997 and his Ph.D. (Dr.-Ing.) in Electrical Engineering from the Technical University Berlin, Germany in 2002 for quality of service support in wireless CDMA networks. As a visiting student at the Arizona State University he conducted research in the field of video services over wireless networks. He co-founded the start-up company acticom GmbH in Berlin in 1999. In 2002 he was Adjunct Professor at the University of Ferrara, Italy giving lectures on wireless communications and conducting research on multi-hop networks. In 2005 he won the YRP award for the work on MIMO MDC and received the Young Elite Researcher Award of Denmark. Due to his “outstanding skills and devotion” he was selected to receive the NOKIA Champion Award in 2007 and 2008. His current research interests are in the areas of wireless and mobile communication networks, mobile phone programming, cross layer as well as energy efficient protocol design and cooperative networking.

Patrick C. F. Eggers (M.Sc.E.E., Ph.D.) is an associate professor and since 1992 has been the project leader of the propagation group of the Center for Person Kommunikation (CPK). He is now the deputy head of the Antennas, Propagation and Radio Networking Section, Department of Electronic Systems, Aalborg University (AAU). He has been project and work package manager in several European research projects (TSUNAMI, CELLO, etc.), and in industrial projects with partners such as Nokia, Ericsson, Motorola, IOSpan, Array-Comm, Avendo Wireless, Samsung, and so on. He is the author of over 40 papers and six patent applications, as well as section author and chapter editor in different COST final reports (COST207, 231, 259) and books on ultra wideband and cooperative communication.