Uplink Coordinated Multi-Point ARQ in MIMO Cellular Systems

Tony Q. S. QUEK[†a)], *Member*, Kampol WORADIT[††b)], Hyundong SHIN[†††c)], *and* Zander LEI[†d)], *Nonmembers*

SUMMARY   Coordinated multi-point processing at multiple base stations can improve coverage, system throughput, and cell-edge throughput for future cellular systems. In this paper, we study the coordinated reception of transmitted signals at multiple MIMO base stations to exploit cooperative diversity. In particular, we propose to employ cooperative multicell automatic repeat request (ARQ) protocol via backhaul links. The attractiveness of this protocol is that processing between coordinated base stations can be made completely transparent to the mobile user, and it improves the mobile user's link reliability and throughput significantly compared to noncooperative ARQ protocol. In our proposed protocol, we consider the scenario where the multicell processing involves one of the following three schemes: decode-and-forward, amplify-and-forward, and compress-and-forward schemes. We derive the average packet error rate and throughput for these cooperative multicell ARQ protocols. Numerical results show that the cooperative multicell ARQ protocols are promising in terms of average packet error rate and throughput. Furthermore, we show that the degree of improvement depends on the type of cooperative multicell ARQ protocol employed and the operating average signal-to-noise ratio of the main and backhaul links.

key words: *multicell processing, uplink, coordinated multi-point reception, cooperative automatic repeat request (ARQ), backhaul links*

1. Introduction

Coordinated multi-point processing (CoMP) at multiple base stations (BSs) has been proposed as a promising technology for improving spectral efficiency, coverage, and cell-edge throughput for future cellular systems [1]–[3]. The basic idea of CoMP is to allow multiple BSs to cooperate via backhaul links to enhance the reliability of the links between mobile user and the serving BS. The inter-cell interference, which usually degrades wireless transmissions, can then be exploited to benefit the transmissions in the case of CoMP. In general, CoMP has two different architectures, namely, centralized and distributed CoMP [4], [5]. The centralized approach needs a central entity that gath-

ers information from all coordinated BSs as well as manages resource allocation, such as scheduling and precoding. The distributed approach assumes that resource allocation is determined locally at each BS and this information is exchanged among BSs via backhaul links.

In downlink CoMP, signal processing can be performed for coordinated transmission by multiple cells to multiple users [5]–[9]. There are two signal processing categories: coordinated scheduling/coordinated beamforming (CS/CB) and joint processing. The basic idea of CS/CB is to transmit a subframe from one cell to a user, where coordinated beamforming and scheduling are performed among cells to reduce the interference to other cells. Unlike CS/CB, the main idea of the joint processing is to transmit signals from multiple cells to a user using the same time and frequency. While the downlink CoMP requires changes in the radio specification and complicated signal processing, the uplink CoMP is simple and can be implemented straightforwardly because of the broadcasting nature of the wireless communications. In uplink CoMP, multiple BSs are allowed to receive the signals transmitted from a user and it usually involves the exchange of decoded signals or un-decoded signals via backhaul links to the serving BS, which performs some joint processing of the aggregate received signals [10]–[12].

1.1   Related Work

Cooperative diversity has recently emerged as one of the most promising enabling technologies, as it is able to address a wide range of application scenarios, including cellular networks, IEEE 802.11 networks, wireless sensor networks, and ad-hoc networks, to enhance connectivity, extend coverage, and improve energy efficiency and/or communication reliability [13]–[25]. In these cooperative networks, the main feature is that relays pool their resources in a distributed manner to enhance the reliability of wireless transmission links. For example, several access points in WLAN may cooperate to receive the uplink signals from the same user [26]. As another example, while one of the nodes is the data source, other nodes try to forward the data to the destination node [27]. In this case, if the cooperative nodes do not forward the data via orthogonal channels, the interference will deteriorate the transmission performance. This problem can be solved by selecting some of them to forward the data and keeping other nodes silent [28], or selecting only the best node to forward the data [29]. A different approach of cooperation is proposed in [30], where

the data is encoded and spliced systematically into multiple parts, each of which is forwarded by distinct relay nodes. Forwarding the data via orthogonal channels does not cause interference, however, additional channel resources, such as time slots, frequency, or antennas, are used. This in turn decreases the gain from employing cooperative diversity. To make the most of this trade-off, network coding may be applied in forwarding the data [31]. The cross-layer consideration is addressed in [32] to improve the cooperation concept from physical layer to networking protocols, where the demonstration is done by incrementally deploying the protocols on the existing commercial hardwares, which are IEEE 802.11b network interface cards. However, the receiver combining cannot be implemented due to the limitation in accessing the firmware on the chip. Based on the relaying concept, the information forwarding is extended to multihop relaying in [33], where the data is passed over cells via wireless channels. This is a cost-effective way to enhance the coverage, throughput, and capacity for rural areas.

Automatic repeat request (ARQ) is a protocol that the receiver requests retransmissions from the transmitter only for the packets that are received erroneously, and these errors can usually be detected by using cyclic redundancy check (CRC) attached with the transmitted packets [34], [35]. Since retransmissions are requested only when necessary, the error rate can be reduced while keeping the latency as small as possible. However, as long as the channel statistics remains unchanged during retransmissions, ARQ is still unable to exploit the time diversity needed to mitigate the channel fading. Therefore, other form of diversity should be combined with ARQ protocol. As a result, there has been much work that combines ARQ protocol at the data link layer and cooperative diversity at the physical layer [36]–[41].

1.2 Main Contributions

In this paper, we study the cooperative reception at multiple MIMO BSs to exploit cooperative diversity. Specifically, we propose to employ cooperative multicell ARQ via backhaul links, where the backhaul links are assumed to have low latency and high capacity [3]. In this way, the processing between cooperative BSs can be made completely transparent to the mobile user, while the reliability and throughput of the mobile user's link is significantly improved compared to noncooperative ARQ protocol. In our proposed protocol, we consider several scenarios where the cooperative BS employs different type of multicell processing, namely, decode-and-forward (DF), amplify-and-forward (AF), and compress-and-forward (CF). For each multicell processing scheme, we derive the corresponding average packet error rate (PER) and throughput. In the DF case, we further consider the situation when BSs do not have perfect channel state information (CSI) for decoding and derive the corresponding average PER[†]. Numerical results show that our cooperative multicell ARQ protocols can significantly reduce the average PER compared to conventional ARQ protocol.

In addition, we show that the degree of improvement depends on the type of multicell processing and the operating average signal-to-noise ratio (SNR) of the main and backhaul links. Moreover, we compare the performance of our proposed protocols with respect to different receiver antenna numbers and cooperative BS numbers.

The paper is organized as follows. In Sect. 2, we introduce the system model and describe all cooperative multicell ARQ protocols. The performance analysis of the proposed protocols in terms of average PER and throughput is presented in Sects. 3 and 4, respectively. For DF processing, the effect of imperfect CSI at BSs is analyzed in Sect. 5. In Sect. 6, we present some numerical results. Finally, we give our conclusion in Sect. 7.

2. System Model

We consider the uplink transmissions in a multi-cell network with a frequency reuse factor of $\frac{1}{K+1}$[††]. Figure 1 illustrates the uplink CoMP for $K = 2$. Each BS is equipped with M antennas and there exists one or more wired backhaul links between each BS, where each backhaul link is modeled as an additive white Gaussian noise (AWGN) channel model. With such frequency planning, neighboring cells are assigned with different frequencies. However, we assume that the BS in each cell can still receive signals from the mobile users in neighboring cells when they are in uplink CoMP mode. That is, when a single source terminal (mobile user) transmits a packet to its serving BS, this packet can also be received at K neighboring BSs.

In the first time slot, the source terminal transmits a packet to its serving BS. The ith symbol in the nth packet received at the serving BS and K neighboring BSs can be
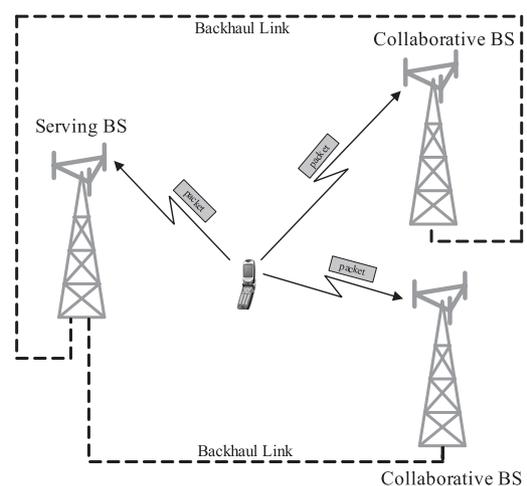

Fig. 1 Uplink CoMP for three cells.

[†]The motivation for considering this scenario is due to the requirement of CSI at cooperative BSs for the DF multicell processing.

[††]Note that our proposed schemes can also be implemented with other form of reuse schemes by carefully taking into account the effect of intercell interference.

written as

$$r_m[i,n] = \sqrt{E_s} h_m[n] x[i,n] + z_m[i,n], m \in \mathcal{M}, \quad (1)$$

$$r_{m,k}[i,n] = \sqrt{E_s} h_{m,k}[n] x[i,n] + z_{m,k}[i,n],$$
$$m \in \mathcal{M}, k \in \mathcal{K} \quad (2)$$

where $\mathcal{K} \triangleq \{1, 2, \ldots, K\}$, $\mathcal{M} \triangleq \{1, 2, \ldots, M\}$, $r_m[i,n]$, and $r_{m,k}[i,n]$ denote the complex baseband equivalent received signals at the mth antenna in the serving BS and the kth neighboring BS, respectively, and $x[i,n]$ denotes the ith transmitted symbol in the nth packet with energy E_s. The complex circularly symmetric Gaussian noise at the mth antenna of the serving BS and the kth neighboring BS are denoted by $z_m[i,n] \sim \mathcal{CN}(0, N_0)$ and $z_{m,k}[i,n] \sim \mathcal{CN}(0, N_0)$, respectively[†]. The complex channel coefficients from the source terminal to the mth antenna of its serving BS and the kth neighboring BS are denoted by $h_m[n] \sim \mathcal{CN}(0, \sigma_s^2)$ and $h_{m,k}[n] \sim \mathcal{CN}(0, \sigma_k^2)$, respectively[††], and are assumed to be constant throughout the packet[††]. By denoting the instantaneous received SNRs at the mth antenna of the serving BS and the kth neighboring BS as $\gamma_{m,s} \triangleq E_s |h_m[n]|^2 / N_0$ and $\gamma_{m,k} \triangleq E_s |h_{m,k}[n]|^2 / N_0$, we can model $\gamma_{m,s}$ and $\gamma_{m,k}$ as exponentially distributed random variables (r.v.'s) with mean λ_s and λ_k, respectively, i.e., $\gamma_{m,s} \sim \mathcal{E}(1/\lambda_s)$, $\gamma_{m,k} \sim \mathcal{E}(1/\lambda_k)$, $\lambda_s = E_s \sigma_s^2 / N_0$, and $\lambda_k = E_s \sigma_k^2 / N_0$[†††]. To enhance the reliability of packet transmissions, we employ several ARQ protocols, including conventional ARQ and cooperative multicell ARQ protocols, as described below.

2.1 Protocol I: No Cooperation

As illustrated in Fig. 2, this is the conventional ARQ protocol, which does not exploit multiple BS reception. To reduce packet delay and system buffer size, we employ truncated ARQ that limits the number of maximum retransmission attempts, which is denoted as N_t [34], [35]. At the end of the first time slot, only the serving BS uses the CRC bits attached with the transmitted packet to check if the r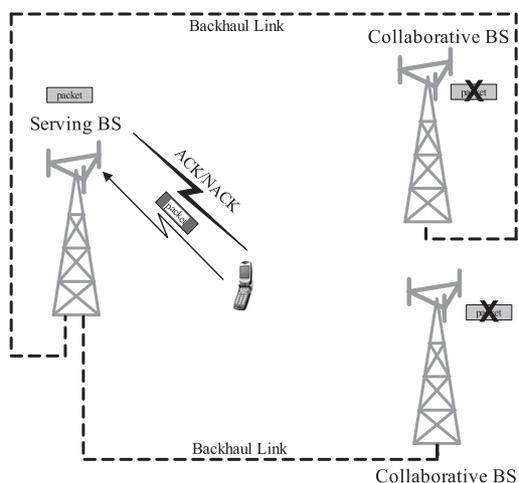eceived packet is received correctly after maximal ratio combining (MRC). If no error is detected in the packet, the serving BS sends an one-bit acknowledgment (ACK) message to the source terminal, indicating successful reception of the packet. Otherwise, an one-bit negative-acknowledgment (NACK) message is sent[††††]. The source terminal continues to retransmit the packet until it reaches N_t retransmission attempts. Throughout this process, the packets received at the K neighboring BSs are deleted upon reception without any multicell processing.

2.2 Protocol II: DF

As illustrated in Fig. 3, this protocol takes advantage of the broadcast nature of uplink transmissions to reach neighboring BSs. With CRC to facilitate error detection, the neighboring BSs can check if they have correctly received their packets after MRC. Only those neighboring BSs that have correctly received the packet are required to participate in the retransmission phase via dedicated backhaul links, thereby keeping the amount of backhaul traffic as small as possible. However, the backhaul latency requirement needs to take into account decoding time at each participating BS. For convenience, we referred to these participating BSs as the cooperative BSs, where the number of cooperative BSs is given by $|\mathcal{K}_c|$ such that $\mathcal{K}_c \subseteq \mathcal{K}$.

At the end of the first time slot, an ACK/NACK message is sent to the source terminal and the K neighboring BSs, depending on the success or failure of the transmission at the serving BS. Upon reception of an ACK at the source terminal and the cooperative BSs, the source terminal transmits a new packet in the next data slot and all
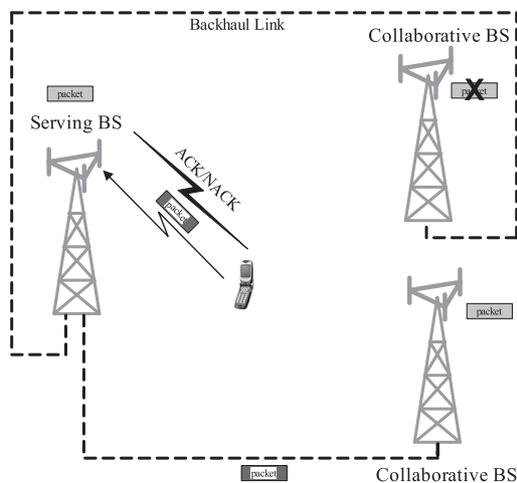
Fig. 3   Protocol II: DF.

[†]$\mathcal{CN}(\mu, \sigma^2)$ denotes a complex circularly symmetric Gaussian distribution with mean μ and variance σ^2.

[††]Note that these variances capture both the effects of path-loss and shadowing.

[†††]We have used the notation $X \sim \mathcal{E}(\lambda)$ to denote that X is exponentially distributed with a constant hazard rate $\lambda > 0$.

[††††]Note that the ACK/NACK messages are one-bit messages. Their error and delay are neglected here.

Fig. 2   Protocol I: No Cooperation.

stored packets at the cooperative BSs are deleted. Otherwise, the source terminal and the cooperative BSs continue to retransmit their packets until N_t retransmission attempts are reached. In the retransmission phase, the cooperative BSs retransmit their packets to the serving BS via dedicated wired backhaul links. The ith symbol in the nth packet received at the serving BS from the kth cooperative BS is given by

$$r_{\text{b},k}^{(\text{II})}[i,n] = \sqrt{G_k E_\text{s}}x[i,n] + z_{\text{b},k}[i,n], k \in \mathcal{K}_\text{c} \qquad (3)$$

where $r_{\text{b},k}^{(\text{II})}[i,n]$ denotes the complex baseband equivalent received signal in the serving BS via the kth backhaul link using protocol II, G_k denotes the channel gain of the kth backhaul link, and $z_{\text{b},k}[i,n] \sim \mathcal{CN}(0, N_0)$. The received SNR at the serving BS via the kth backhaul link is denoted as $\gamma_{\text{b},k} \triangleq G_k E_\text{s}/N_0$.

2.3 Protocol III: AF

As illustrated in Fig. 4, all K neighboring BSs always cooperate by forwarding their packets in the retransmission phase. The difference between protocol II and III is that protocol II selectively decodes and forward packets from the neighboring BSs, whereas protocol III forward the received signals from each antenna at the cooperative BS to the serving BS via M dedicated backhaul links. Without any decoding at each cooperative BS, the backhaul latency requirement of protocol III is much shorter at the expense of a larger amount of backhaul traffic.

At the serving BS, the forwarded signals from each cooperative BS are first combined using MRC before decoding. In the retransmission phase, the ith symbol in the nth packet received at the serving BS from the mth antenna of the kth neighboring BS is given by
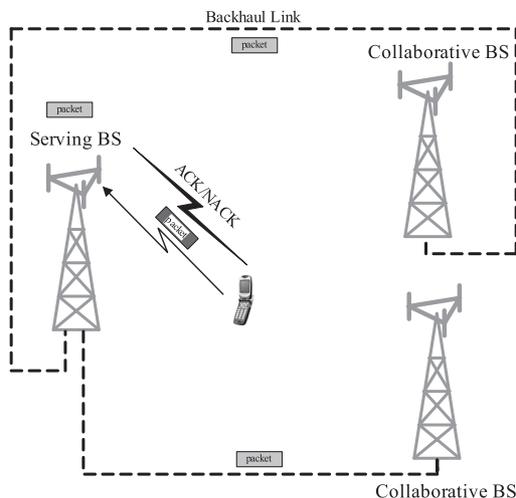

Fig. 4 Protocol III: AF.

$$r_{\text{b},m,k}^{(\text{III})}[i,n] = \alpha_k \sqrt{G_k E_\text{s}}h_{m,k}[n]x[i,n]$$
$$+ \alpha_k \sqrt{G_k}z_{m,k}[i,n]$$
$$+ z_{\text{b},m,k}[i,n], k \in \mathcal{K}, m \in \mathcal{M} \qquad (4)$$

and the normalization factor α_k is given by

$$\alpha_k = \sqrt{\frac{E_\text{s}}{\mathbb{E}\{|h_{m,k}[n]|^2\}E_\text{s} + N_0}}, m \in \mathcal{M} \qquad (5)$$

where $r_{\text{b},m,k}^{(\text{III})}[i,n]$ denotes the complex baseband equivalent received signal in the serving BS using protocol III via the backhaul link for the mth antenna of the kth neighboring BS, and $z_{\text{b},m,k}[i,n] \sim \mathcal{CN}(0, N_0)$. Thus, the effective instantaneous received SNR at the serving BS via the backhaul link for the mth antenna of the kth neighboring BS is given by

$$\gamma_{\text{eff},m,k} = \frac{\gamma_{m,k}\gamma_{\text{b},k}}{\lambda_k + \gamma_{\text{b},k} + 1}. \qquad (6)$$

The serving BS combines $r_{\text{b},m,k}^{(\text{III})}[i,n]$ from all M antennas using MRC for decoding.

Remark 1: A variation of protocol III is to combine $r_{m,k}[i,n]$ from all M antennas using MRC before AF processing. This variation as well as its results are not presented here because its performance is less attractive due to the normalization in AF processing that reduces the effective received SNR at the serving BS.

2.4 Protocol IV: CF

In protocol IV, every neighboring BS performs CF and does not exploit the direct reception at the serving BS, namely, using the standard rate-distortion scheme. Similar to Fig. 4, all K neighboring BSs always cooperate by compressing their packets in the retransmission phase. Compared to protocol III, the backhaul latency requirement of protocol IV is slightly longer due to compression, but the amount of backhaul traffic is reduced. Even though this scheme is suboptimal, it has lower decoding complexity and is much easier to implement in practice [42], [43].

To compress the packet separately among BSs, the kth neighboring BS first combines the received signals in (2) to give

$$r_k[i,n] = \sqrt{E_\text{s}}\sum_{m=1}^{M}|h_{m,k}[n]|^2 x[i,n]$$
$$+ \sum_{m=1}^{M}h_{m,k}^*[n]z_{m,k}[i,n], k \in \mathcal{K} \qquad (7)$$

and normalizes the combined signal with the normalization factor

$$\beta_k[n] =$$
$$\sqrt{\frac{1}{E_\text{s}\left(\sum_{m=1}^{M}|h_{m,k}[n]|^2\right)^2 + N_0\sum_{m=1}^{M}|h_{m,k}[n]|^2}} \qquad (8)$$

where $r_k[i, n]$ denotes the MRC processed signal at the kth neighboring BS, and $*$ is the complex conjugate operator. Then, the ith symbol in the packet becomes $\beta_k[n]r_k[i, n]$ and is quantized at a rate R_k. In the retransmission phase, the ith symbol in the nth packet received at the serving BS from the kth neighboring BS is given by

$$
\begin{aligned}
r_{\mathrm{b},k}^{(\mathrm{IV})}[i, n] =& \beta_k[n] \sqrt{G_k E_s} \sum_{m=1}^{M} |h_{m,k}[n]|^2 x[i, n] \\
&+ \beta_k[n] \sqrt{G_k} \sum_{m=1}^{M} h_{m,k}^*[n] z_{m,k}[i, n] \\
&+ z_{\mathrm{q},k}[i, n], \quad k \in \mathcal{K}
\end{aligned}
\tag{9}
$$

where $r_{\mathrm{b},k}^{(\mathrm{IV})}[i, n]$ denotes the complex baseband equivalent received signal in the serving BS using protocol IV via the backhaul link of the kth neighboring BS and the quantization noise is denoted by $z_{\mathrm{q},k}[i, n] \sim \mathcal{CN}(0, \sigma_{\mathrm{q},k}^2)$, where $\sigma_{\mathrm{q},k}^2 = 1/(2^{R_k} - 1)$. The effective instantaneous received SNR at the serving BS via the backhaul link of the kth neighboring BS can be expressed as

$$
\gamma_{\mathrm{q,eff},k} = \frac{\gamma_k \eta_k}{\gamma_k + \eta_k + 1}
\tag{10}
$$

where $\gamma_k \triangleq E_s \sum_{m=1}^{M} |h_{m,k}[n]|^2 / N_0$ denotes the instantaneous received SNR at the kth neighboring BS after MRC and $\eta_k \triangleq 1/\sigma_{\mathrm{q},k}^2 = 2^{R_k} - 1$.

3. Average Packet Error Rate Analysis

In the following, we first derive the average PER for each protocol described in Sect. 2. Due to the latency constraint and overhead on backhaul requirements, we restrict all retransmissions to $N_t = 1$[†].

3.1 Protocol I: No Cooperation

By denoting the instantaneous received SNR at the serving BS after MRC as $\gamma_{\mathrm{s}} \triangleq E_s \sum_{m=1}^{M} |h_m[n]|^2 / N_0$, we can model γ_{s} as a gamma distributed r.v. with mean $M\lambda_{\mathrm{s}}$, i.e. $\gamma_{\mathrm{s}} \sim \Gamma(M, \lambda_{\mathrm{s}})$[††]. The probability density function (pdf) of a gamma distributed r.v. with shape parameter M and scale parameter λ is given by [44]

$$
p_{\Gamma}(\gamma; M, \lambda) = \frac{\gamma^{M-1} \exp\left(-\frac{\gamma}{\lambda}\right)}{\lambda^M (M-1)!}.
\tag{11}
$$

In addition, the PER conditioned on the channel can be approximated as [35]

$$
\mathrm{PER}(\gamma_{\mathrm{s}}) \approx
\begin{cases}
1, & \text{if } 0 \le \gamma_{\mathrm{s}} < \gamma_t, \\
\alpha \exp(-g\gamma_{\mathrm{s}}) & \text{if } \gamma_{\mathrm{s}} \ge \gamma_t
\end{cases}
\tag{12}
$$

where α, g, and γ_t are parameters that depend on the type of modulation and coding scheme, and $\alpha \exp(-g\gamma_t) = 1$ [35]. Since the retransmission occurs immediately, the instantaneous SNR does not change and the conditional PER

of protocol I is given by

$$
\mathrm{PER}^{(\mathrm{I})}(\gamma_{\mathrm{s}}) = (\mathrm{PER}(\gamma_{\mathrm{s}}))^2
\tag{13}
$$

By taking the expectation of the function in (12) with respect to the PDF in (11) with $\lambda = \lambda_s$, we obtain the average PER of protocol I as follows:

$$
\begin{aligned}
\overline{\mathrm{PER}}^{(\mathrm{I})} =& \mathbb{E}\left\{(\mathrm{PER}(\gamma_{\mathrm{s}}))^2\right\} = 1 - \exp\left(-\frac{\gamma_t}{\lambda_{\mathrm{s}}}\right) \\
&\sum_{m=0}^{M-1} \frac{1}{m!} \left(\frac{\gamma_t}{\lambda_{\mathrm{s}}}\right)^m \left[1 - \frac{1}{(1 + 2g\lambda_{\mathrm{s}})^{M-m}}\right].
\end{aligned}
\tag{14}
$$

3.2 Protocol II: DF

By denoting the instantaneous received SNR at the kth neighboring BS after MRC as $\gamma_k \triangleq E_s \sum_{m=1}^{M} |h_{m,k}[n]|^2 / N_0$, we can model $\gamma_k \sim \Gamma(M, \lambda_k)$. Using the approximation in (12), the approximate conditional PER at the kth neighboring BS is given by $\mathrm{PER}(\gamma_k)$ and the average PER of the kth neighboring BS can be written as

$$
\begin{aligned}
\mathbb{E}\{\mathrm{PER}(\gamma_k)\} =& 1 - \exp\left(-\frac{\gamma_t}{\lambda_k}\right) \sum_{m=0}^{M-1} \frac{1}{m!} \left(\frac{\gamma_t}{\lambda_k}\right)^m \\
&\left[1 - \frac{1}{(1 + g\lambda_k)^{M-m}}\right].
\end{aligned}
\tag{15}
$$

In addition, the approximate conditional PER associated with the retransmission from the kth neighboring BS to the serving BS via its backhaul link can also be approximated as [35]

$$
\mathrm{PER}(\gamma_{\mathrm{b},k}) \approx
\begin{cases}
1, & 0 \le \gamma_{\mathrm{b},k} < \gamma_t, \\
\alpha \exp(-g\gamma_{\mathrm{b},k}), & \gamma_{\mathrm{b},k} \ge \gamma_t.
\end{cases}
\tag{16}
$$

Consider that only a subset of neighboring BSs, i.e., $\mathcal{K}_c$, received the packet correctly from the source terminal with probability given by

$$
\Pr\{\mathcal{K}_c\} = \prod_{k \in \mathcal{K}_c} (1 - \mathrm{PER}(\gamma_k)) \prod_{k' \in \mathcal{K} \backslash \mathcal{K}_c} \mathrm{PER}(\gamma_{k'}).
\tag{17}
$$

Recall that these neighboring BSs are referred to as cooperative BSs, the probability that all the cooperative BSs retransmit their packets to the serving BS with error is given by

$$
\Pr\{\text{backhaul error}|\mathcal{K}_c\} = \prod_{k \in \mathcal{K}_c} \mathrm{PER}(\gamma_{\mathrm{b},k}).
\tag{18}
$$

From (17) and (18), the probability that no neighboring BS

[†]Note that the extension to $N_t > 1$ is straightforward.

[††]We have used the notation $X \sim \Gamma(M, \lambda)$ to denote that X is gamma distributed with a shape parameter $M > 0$ and a scale parameter $\lambda > 0$. In this paper, the shape parameter M is an integer, which is the number of antennas at each BS.

can successfully retransmit a packet from the source terminal to the serving BS is given by

$$\Pr\{\text{backhaul error}\}$$

$$= \sum_{|\mathcal{K}_c|=0}^{K} \sum_{\mathcal{K}_c} \Pr\{\mathcal{K}_c\} \Pr\{\text{backhaul error}|\mathcal{K}_c\}$$

$$= \sum_{|\mathcal{K}_c|=0}^{K} \sum_{\mathcal{K}_c} \left\{ \prod_{k \in \mathcal{K}_c} (1 - \text{PER}(\gamma_k)) \, \text{PER}(\gamma_{\text{b},k}) \right. $$

$$\left. \prod_{k' \in \mathcal{K} \setminus \mathcal{K}_c} \text{PER}(\gamma_{k'}) \right\}, \tag{19}$$

where the outer summation is taken among different cardinalities of the set $\mathcal{K}_c$ from 0 until K. Therefore, the average PER of protocol II is given by

$$\overline{\text{PER}}^{(\text{II})}$$

$$= \mathbb{E}\left\{ \text{PER}^{(\text{II})}(\gamma_{\text{s}}, \gamma_1, \ldots, \gamma_K, \gamma_{\text{b},1}, \ldots, \gamma_{\text{b},K}) \right\}$$

$$= \mathbb{E}\left\{ (\text{PER}(\gamma_{\text{s}}))^2 \right\} \sum_{|\mathcal{K}_c|=0}^{K} \sum_{\mathcal{K}_c} \left\{ \prod_{k \in \mathcal{K}_c} (1 - \mathbb{E}\{\text{PER}(\gamma_k)\}) \right.$$

$$\left. \text{PER}(\gamma_{\text{b},k}) \prod_{k' \in \mathcal{K} \setminus \mathcal{K}_c} \mathbb{E}\{\text{PER}(\gamma_{k'})\} \right\}$$

$$= \left(1 - \exp\left(-\frac{\gamma_t}{\lambda_{\text{s}}} \right) \sum_{m=0}^{M-1} \frac{1}{m!} \left(\frac{\gamma_t}{\lambda_{\text{s}}} \right)^m \right.$$

$$\left. \left[1 - \frac{1}{(1 + 2g\lambda_{\text{s}})^{M-m}} \right] \right) \sum_{|\mathcal{K}_c|=0}^{K} \sum_{\mathcal{K}_c} \left\{ \prod_{k \in \mathcal{K}_c} \exp\left(-\frac{\gamma_t}{\lambda_k} \right) \right.$$

$$\sum_{m=0}^{M-1} \frac{1}{m!} \left(\frac{\gamma_t}{\lambda_k} \right)^m \left[1 - \frac{1}{(1 + g\lambda_k)^{M-m}} \right] \text{PER}(\gamma_{\text{b},k})$$

$$\prod_{k' \in \mathcal{K} \setminus \mathcal{K}_c} \left(1 - \exp\left(-\frac{\gamma_t}{\lambda_{k'}} \right) \sum_{m=0}^{M-1} \frac{1}{m!} \left(\frac{\gamma_t}{\lambda_{k'}} \right)^m \right.$$

$$\left. \left. \left[1 - \frac{1}{(1 + g\lambda_{k'})^{M-m}} \right] \right) \right\}. \tag{20}$$

3.3 Protocol III: AF

By denoting the effective instantaneous received SNR at the serving BS via the kth neighboring BS after MRC as $\gamma_{\text{eff},k} \triangleq \sum_{m=1}^{M} \gamma_{\text{eff},m,k}$, we can characterize $\gamma_{\text{eff},k}$ statistically in the following lemma.

Lemma 1: The pdf of $\gamma_{\text{eff},k}$ from the kth neighboring BS after MRC at the serving BS is given by

$$p_{\gamma_{\text{eff},k}}(\gamma) = \left(\frac{\lambda_k + \gamma_{\text{b},k} + 1}{\lambda_k \gamma_{\text{b},k}} \right)^M$$

$$\exp\left(-\frac{\lambda_k + \gamma_{\text{b},k} + 1}{\lambda_k \gamma_{\text{b},k}} \gamma \right) \frac{\gamma^{M-1}}{(M-1)!}. \tag{21}$$

Proof 1: From (6), we have

$$\gamma_{m,k} = \frac{\lambda_k + \gamma_{\text{b},k} + 1}{\gamma_{\text{b},k}} \gamma_{\text{eff},m,k}. \tag{22}$$

By summing both the left and right-hand sides of (22) over all m, we have

$$\gamma_k = \frac{\lambda_k + \gamma_{\text{b},k} + 1}{\gamma_{\text{b},k}} \gamma_{\text{eff},k} \tag{23}$$

and taking the jacobian of γ_k with respect to $\gamma_{\text{eff},k}$, we obtain

$$\left| \frac{d\gamma_k}{d\gamma_{\text{eff},k}} \right| = \frac{\lambda_k + \gamma_{\text{b},k} + 1}{\gamma_{\text{b},k}}. \tag{24}$$

From (23) we obtain the pdf of $\gamma_{\text{eff},k}$ since γ_k is a linear function of $\gamma_{\text{eff},k}$ and the pdf of γ_k is known [45].

Similar to (12), the conditional PER of the packet forwarded from the kth neighboring BS can be approximated as

$$\text{PER}(\gamma_{\text{eff},k}) \approx \begin{cases} 1, & 0 \le \gamma_{\text{eff},k} < \gamma_t, \\ \alpha \exp\left(-g\gamma_{\text{eff},k} \right), & \gamma_{\text{eff},k} \ge \gamma_t \end{cases} \tag{25}$$

and the corresponding average PER using Lemma 1 is given by

$$\mathbb{E}\{\text{PER}(\gamma_{\text{eff},k})\} = \int_0^{\gamma_t} p_{\gamma_{\text{eff},k}}(\gamma) \, d\gamma$$

$$+ \int_{\gamma_t}^{\infty} \alpha \exp\left(-g\gamma \right) p_{\gamma_{\text{eff},k}}(\gamma) \, d\gamma \tag{26}$$

where

$$\int_0^{\gamma_t} p_{\gamma_{\text{eff},k}}(\gamma) \, d\gamma = 1 - \exp\left(-\frac{\lambda_k + \gamma_{\text{b},k} + 1}{\lambda_k \gamma_{\text{b},k}} \gamma_t \right)$$

$$\sum_{m=0}^{M-1} \frac{1}{m!} \left(\frac{\lambda_k + \gamma_{\text{b},k} + 1}{\lambda_k \gamma_{\text{b},k}} \gamma_t \right)^m \tag{27}$$

and

$$\int_{\gamma_t}^{\infty} \alpha \exp\left(-g\gamma \right) p_{\gamma_{\text{eff},k}}(\gamma) \, d\gamma$$

$$= \exp\left(-\frac{\lambda_k + \gamma_{\text{b},k} + 1}{\lambda_k \gamma_{\text{b},k}} \gamma_t \right) \sum_{m=0}^{M-1} \frac{1}{m!}$$

$$\left(\frac{\lambda_k + \gamma_{\text{b},k} + 1}{\lambda_k \gamma_{\text{b},k}} \gamma_t \right)^m \frac{1}{\left(1 + \frac{g\lambda_k \gamma_{\text{b},k}}{\lambda_k + \gamma_{\text{b},k} + 1} \right)^{M-m}}. \tag{28}$$

Using (14) and (26), the average PER of protocol III is given by

$$\overline{\mathsf{PER}}^{(\mathrm{III})} = \mathbb{E}\left\{\mathsf{PER}^{(\mathrm{III})}(\gamma_s, \gamma_{\mathrm{eff},1}, \ldots, \gamma_{\mathrm{eff},K})\right\}$$

$$= \mathbb{E}\left\{(\mathsf{PER}(\gamma_s))^2\right\} \prod_{k \in \mathcal{K}} \mathbb{E}\left\{\mathsf{PER}(\gamma_{\mathrm{eff},k})\right\}$$

$$= \left(1 - \exp\left(-\frac{\gamma_t}{\lambda_s}\right) \sum_{m=0}^{M-1} \frac{1}{m!} \left(\frac{\gamma_t}{\lambda_s}\right)^m \right.$$

$$\left[1 - \frac{1}{(1 + 2g\lambda_s)^{M-m}}\right] \prod_{k \in \mathcal{K}} \left\{1\right.$$

$$- \exp\left(-\frac{\lambda_k + \gamma_{b,k} + 1}{\lambda_k \gamma_{b,k}}\gamma_t\right) \sum_{m=0}^{M-1} \frac{1}{m!}$$

$$\left.\left.\left(\frac{\lambda_k + \gamma_{b,k} + 1}{\lambda_k \gamma_{b,k}}\gamma_t\right)^m \left[1 - \frac{1}{\left(1 + \frac{g\lambda_k \gamma_{b,k}}{\lambda_k + \gamma_{b,k} + 1}\right)^{M-m}}\right]\right\}\right). \qquad (29)$$

3.4 Protocol IV: CF

We can characterize $\gamma_{q,\mathrm{eff},k}$, which is the effective instantaneous received SNR at the serving BS via the kth neighboring BS given in (10), statistically in the following lemma.

Lemma 2: The pdf of $\gamma_{q,\mathrm{eff},k}$ from the kth neighboring BS at the serving BS is given by

$$p_{\gamma_{q,\mathrm{eff},k}}(\gamma) = \frac{\eta_k}{(\eta_k - \gamma)\gamma(M-1)!} \left(\frac{(\eta_k + 1)\gamma}{(\eta_k - \gamma)\lambda_k}\right)^M$$

$$\exp\left(-\frac{(\eta_k + 1)\gamma}{(\eta_k - \gamma)\lambda_k}\right), 0 \le \gamma < \eta_k. \qquad (30)$$

Proof 2: Following the proof for Lemma 1, we first derive

$$\gamma_k = \frac{(\eta_k + 1)\gamma_{q,\mathrm{eff},k}}{\eta_k - \gamma_{q,\mathrm{eff},k}} \qquad (31)$$

and the jacobian of γ_k with respect to $\gamma_{q,\mathrm{eff},k}$ as follows:

$$\left|\frac{d\gamma_k}{d\gamma_{q,\mathrm{eff},k}}\right| = \frac{\eta_k(\eta_k + 1)}{(\eta_k - \gamma_{q,\mathrm{eff},k})^2}. \qquad (32)$$

Straightforwardly, we can yield (30) using similar approach as in the proof of Lemma 1.

Similar to (12), the conditional PER of the quantized packet from the kth neighboring BS can be approximated as

$$\mathsf{PER}(\gamma_{q,\mathrm{eff},k}) \approx \begin{cases} 1, & 0 \le \gamma_{\mathrm{eff},k} < \gamma_t \\ \alpha \exp\left(-g\gamma_{q,\mathrm{eff},k}\right), & \gamma_t \le \gamma_{\mathrm{eff},k} < \eta_k \end{cases} \qquad (33)$$

and the corresponding average PER is given by

$$\mathbb{E}\left\{\mathsf{PER}(\gamma_{q,\mathrm{eff},k})\right\} =$$

$$\begin{cases} 1, & \eta_k \le \gamma_t, \\ \int_0^{\gamma_t} p_{\gamma_{q,\mathrm{eff},k}}(\gamma)\,d\gamma \\ + \int_{\gamma_t}^{\eta_k} \alpha \exp\left(-g\gamma\right) p_{\gamma_{q,\mathrm{eff},k}}(\gamma)\,d\gamma, & \eta_k > \gamma_t. \end{cases} \qquad (34)$$

Suppose $\eta_k > \gamma_t$. From Lemma 2, the first integral in (34) can be written as

$$\int_0^{\gamma_t} p_{\gamma_{q,\mathrm{eff},k}}(\gamma)\,d\gamma$$

$$= \int_0^{\frac{(\eta_k+1)\gamma_t}{(\eta_k - \gamma_t)\lambda_k}} \frac{w^{M-1}\exp(-w)}{(M-1)!}\,dw$$

$$= 1 - \exp\left(-\frac{(\eta_k + 1)\gamma_t}{(\eta_k - \gamma_t)\lambda_k}\right) \sum_{m=0}^{M-1} \frac{1}{m!} \left(\frac{(\eta_k + 1)\gamma_t}{(\eta_k - \gamma_t)\lambda_k}\right)^m \qquad (35)$$

where w is a transformation from γ and is defined as

$$w = \frac{(\eta_k + 1)}{\left(\frac{\eta_k}{\gamma} - 1\right)\lambda_k}. \qquad (36)$$

Also, the second integral in (34) can be expressed as

$$\int_{\gamma_t}^{\eta_k} \alpha \exp\left(-g\gamma\right) p_{\gamma_{q,\mathrm{eff},k}}(\gamma)\,d\gamma$$

$$= \int_{\gamma_t}^{\eta_k} \alpha \exp(-g\gamma) \frac{\eta_k}{(\eta_k - \gamma)\gamma(M-1)!}$$

$$\left(\frac{(\eta_k + 1)\gamma}{(\eta_k - \gamma)\lambda_k}\right)^M \exp\left(-\frac{(\eta_k + 1)\gamma}{(\eta_k - \gamma)\lambda_k}\right)\,d\gamma. \qquad (37)$$

Since the interval is finite and the integrand is strictly decreasing and converges to 0, the numerical integration can be carried out with convenience and accuracy. By substituting (35) and (37) into (34), the average PER of protocol IV is given by

$$\overline{\mathsf{PER}}^{(\mathrm{IV})} = \mathbb{E}\left\{\mathsf{PER}^{(\mathrm{IV})}(\gamma_s, \gamma_{q,\mathrm{eff},1}, \ldots, \gamma_{q,\mathrm{eff},K})\right\}$$

$$= \mathbb{E}\left\{(\mathsf{PER}(\gamma_s))^2\right\} \prod_{k \in \mathcal{K}} \mathbb{E}\left\{\mathsf{PER}(\gamma_{q,\mathrm{eff},k})\right\}$$

$$= \left(1 - \exp\left(-\frac{\gamma_t}{\lambda_s}\right) \sum_{m=0}^{M-1} \frac{1}{m!} \left(\frac{\gamma_t}{\lambda_s}\right)^m \left[1 - \frac{1}{(1 + 2g\lambda_s)^{M-m}}\right]\right) \prod_{k \in \mathcal{K}} \left\{1 - \exp\left(-\frac{(\eta_k + 1)\gamma_t}{(\eta_k - \gamma_t)\lambda_k}\right)\right.$$

$$\sum_{m=0}^{M-1} \frac{1}{m!} \left(\frac{(\eta_k + 1)\gamma_t}{(\eta_k - \gamma_t)\lambda_k}\right)^m + \int_{\gamma_t}^{\eta_k} \alpha \exp(-g\gamma)$$

$$\frac{\eta_k}{(\eta_k - \gamma)\gamma(M-1)!} \left(\frac{(\eta_k + 1)\gamma}{(\eta_k - \gamma)\lambda_k}\right)^M$$

$$\left.\exp\left(-\frac{(\eta_k + 1)\gamma}{(\eta_k - \gamma)\lambda_k}\right)\,d\gamma\right\} \qquad (38)$$

for $\eta_k > \gamma_t$. Otherwise, $\overline{\mathsf{PER}}^{(\mathrm{IV})} = \mathbb{E}\left\{(\mathsf{PER}(\gamma_s))^2\right\}$ as given in (14).

Remark 2: Note that the backhaul link effects the performance of protocol II or protocol III via $\gamma_{b,k}$ whereas performance of protocol IV depends on R_k, which is the rate of the backhaul link. Therefore, to compare these protocols, we choose R_k for protocol IV such that it corresponds to a certain $\gamma_{b,k}$ of protocol II and protocol III.

4. Average Throughput Analysis

Besides the average PER, the average throughput is another important performance metric of ARQ protocol since it is directly related to the backhaul requirements for our cooperative multicell ARQ protocols. Considering a packet transmission with L bits per packet, C bits of which are CRC, a modulation level for every symbol of b bits per symbol and a coding rate of R, the average throughput of the conventional ARQ protocol in the unit of bits per channel use is given by [38]

$$\mathsf{T} = Rb\frac{L-C}{L}\frac{P_A}{\mathbb{E}\{N_A\}} \tag{39}$$

where P_A is the packet transmission successful rate and $\mathbb{E}\{N_A\}$ is the average number of transmissions per packet. The unit of the defined throughput is in b/s/Hz, which can be larger than 1. Given (39), we can compute the average throughput for our proposed cooperative multicell ARQ protocols discussed in the previous section[†]. Note that the average number of transmissions includes both the wireless transmission from the source terminal to the serving BS and the backhaul transmissions from the neighboring BSs to the serving BS.

4.1 Protocol II: DF

The packet transmission successful rate for protocol II is given by $P_A^{(\text{II})} = 1 - \overline{\mathsf{PER}}^{(\text{II})}$, where $\overline{\mathsf{PER}}^{(\text{II})}$ is given in (20). In protocol II, the main BS can receive a packet from one cooperative BS at a time. Therefore, the number of transmissions per packet can be any number within the set $\{1, 2, \ldots, 2+K\}$, and the average number of transmissions per packet for protocol II can be written as

$$\mathbb{E}\{N_A\}^{(\text{II})} = 1(1 - \overline{\mathsf{PER}}_{\text{s}}) + \overline{\mathsf{PER}}_{\text{s}} \sum_{\kappa=0}^{K}(2+\kappa)$$
$$\sum_{\mathcal{K}_c:|\mathcal{K}_c|=\kappa}\prod_{k\in\mathcal{K}_c}(1-\overline{\mathsf{PER}}_k)\prod_{k'\in\mathcal{K}\backslash\mathcal{K}_c}\overline{\mathsf{PER}}_{k'} \tag{40}$$

where $\overline{\mathsf{PER}}_k$ denotes $\mathbb{E}\{\mathsf{PER}(\gamma_k)\}$ given in (15) and $\overline{\mathsf{PER}}_{\text{s}}$ denotes $\mathbb{E}\{\mathsf{PER}(\gamma_{\text{s}})\}$, which can be straightforwardly obtained from (15) by replacing λ_k with λ_{s}. Therefore, the average throughput of protocol II is given by

$$\mathsf{T}^{(\text{II})} = Rb\frac{L-C}{L}\frac{P_A^{(\text{II})}}{\mathbb{E}\{N_A\}^{(\text{II})}}$$
$$= Rb\frac{L-C}{L}\left(1 - \overline{\mathsf{PER}}^{(\text{II})}\right)\left(1 - \overline{\mathsf{PER}}_{\text{s}} + \overline{\mathsf{PER}}_{\text{s}}\sum_{\kappa=0}^{K}(2\right.$$
$$\left.+\kappa)\sum_{\mathcal{K}_c:|\mathcal{K}_c|=\kappa}\prod_{k\in\mathcal{K}_c}(1-\overline{\mathsf{PER}}_k)\prod_{k'\in\mathcal{K}\backslash\mathcal{K}_c}\overline{\mathsf{PER}}_{k'}\right)^{-1}. \tag{41}$$

4.2 Protocol III: AF

The packet transmission successful rate for protocol III is given by $P_A^{(\text{III})} = 1 - \overline{\mathsf{PER}}^{(\text{III})}$, where $\overline{\mathsf{PER}}^{(\text{III})}$ is given in (29). In protocol III, the number of transmissions per packet can be either 1 or $2 + K$ since all K neighboring BSs forward their packets in the retransmission phase with M antennas in parallel. Thus, the average number of transmissions per packet for protocol III can be expressed as

$$\mathbb{E}\{N_A\}^{(\text{III})} = 1(1 - \overline{\mathsf{PER}}_{\text{s}}) + (2 + K)(\overline{\mathsf{PER}}_{\text{s}}) \tag{42}$$

and the average throughput of protocol III is given by

$$\mathsf{T}^{(\text{III})} = Rb\frac{L-C}{L}\frac{P_A^{(\text{III})}}{\mathbb{E}\{N_A\}^{(\text{III})}}$$
$$= Rb\frac{L-C}{L}\frac{1 - \overline{\mathsf{PER}}^{(\text{III})}}{1 + (1+K)\overline{\mathsf{PER}}_{\text{s}}}. \tag{43}$$

4.3 Protocol IV: CF

The packet transmission successful rate for protocol IV is given by $P_A^{(\text{IV})} = 1 - \overline{\mathsf{PER}}^{(\text{IV})}$, where $\overline{\mathsf{PER}}^{(\text{IV})}$ is given in (38). Due to the similarity to protocol III, the average number of transmissions per packet for protocol IV can also be written as

$$\mathbb{E}\{N_A\}^{(\text{IV})} = 1 + (1 + K)\overline{\mathsf{PER}}_{\text{s}} \tag{44}$$

and the average throughput of protocol IV is given by

$$\mathsf{T}^{(\text{IV})} = Rb\frac{L-C}{L}\frac{P_A^{(\text{IV})}}{\mathbb{E}\{N_A\}^{(\text{IV})}}$$
$$= Rb\frac{L-C}{L}\frac{1 - \overline{\mathsf{PER}}^{(\text{IV})}}{1 + (1+K)\overline{\mathsf{PER}}_{\text{s}}}. \tag{45}$$

5. Effect of Imperfect CSI

In practical systems, the channel resources allocated to BSs for CSI estimation may be limited and BSs may not be able to estimate CSI perfectly [46]. As such, it is important to examine the effect of imperfect CSI at BSs, particularly for protocol II. Before the source terminal transmits a packet, it transmits I_{p} pilot symbols to all BSs. The ith pilot symbol associated with the nth packet received at the mth antenna at the serving BS and K neighboring BSs can be written as

$$r_{\text{p},m}[i, n] = \sqrt{E_{\text{p}}}h_m[n]x_{\text{p}}[i, n] + z_{\text{p},m}[i, n],$$
$$i = 1, \ldots, I_{\text{p}}, m \in \mathcal{M},$$
$$r_{\text{p},m,k}[i, n] = \sqrt{E_{\text{p}}}h_{m,k}[n]x_{\text{p}}[i, n] + z_{\text{p},m,k}[i, n],$$
$$i = 1, \ldots, I_{\text{p}}, m \in \mathcal{M}, k \in \mathcal{K} \tag{46}$$

[†]Note that the average throughput considered here does not differentiate between the wireless and backhaul links.

where $r_{p,m}[i, n]$ denotes the complex baseband equivalent received signal at the mth antenna in the serving BS, $r_{p,m,k}[i, n]$ denotes the complex baseband equivalent received signal at the mth antenna in the kth neighboring BS, $x_p[i, n]$ denotes the ith transmitted pilot symbol in the nth packet with energy E_p, $z_{p,m}[i, n] \sim \mathcal{CN}(0, N_0)$, and $z_{p,m,k}[i, n] \sim \mathcal{CN}(0, N_0)$.

Assuming minimum mean square error estimation, the estimated channel coefficient in the nth packet at the mth antenna is given by [47]

$$\hat{h}_m[n] = \sum_{i=1}^{I_p} \frac{\sigma_s^2 \sqrt{E_p}}{I_p \sigma_s^2 E_p + N_0} r_{p,m}[i, n], \tag{47}$$

$$\hat{h}_{m,k}[n] = \sum_{i=1}^{I_p} \frac{\sigma_k^2 \sqrt{E_p}}{I_p \sigma_k^2 E_p + N_0} r_{p,m,k}[i, n] \tag{48}$$

and the channel estimation mean square error (MSE) can be written as [47]

$$V_s^2 = \frac{\sigma_s^2}{1 + \frac{I_p \sigma_s^2 E_p}{N_0}}, \tag{49}$$

$$V_k^2 = \frac{\sigma_k^2}{1 + \frac{I_p \sigma_k^2 E_p}{N_0}} \tag{50}$$

where $\hat{h}_m[n]$ and $\hat{h}_{m,k}[n]$ can be modeled as the complex Gaussian r.v.'s with distribution $\mathcal{CN}(0, \sigma_s^2 - V_s^2)$ and $\mathcal{CN}(0, \sigma_k^2 - V_k^2)$, respectively. It has been shown in [48] that the effect from the imperfect CSI is equivalent to decreasing the received SNR in decoding with perfect CSI. Specifically, the instantaneous received SNR at the mth antenna of the serving BS and K neighboring BSs become

$$\gamma_{\epsilon,m,s} = \frac{1}{1 + \epsilon_s} \gamma_{m,s}, \quad m \in \mathcal{M}, \tag{51}$$

$$\gamma_{\epsilon,m,k} = \frac{1}{1 + \epsilon_k} \gamma_{m,k}, \quad k \in \mathcal{K}, m \in \mathcal{M} \tag{52}$$

where $\epsilon_s = E_s V_s^2 / N_0$ and $\epsilon_k = E_s V_k^2 / N_0$. We can model $\gamma_{\epsilon,m,s}$ and $\gamma_{\epsilon,m,k}$ as exponentially distributed r.v.'s with mean $\lambda_s / (1 + \epsilon_s)$ and $\lambda_k / (1 + \epsilon_k)$, respectively, i.e., $\gamma_{\epsilon,m,s} \sim \mathcal{E}((1 + \epsilon_s)/\lambda_s)$ and $\gamma_{\epsilon,m,k} \sim \mathcal{E}((1 + \epsilon_k)/\lambda_k)$.

As such, we can model $\gamma_{\epsilon,s}$, which is the instantaneous received SNR at the serving BS after MRC, as a gamma distributed r.v. with mean $M\lambda_s / (1 + \epsilon_s)$, i.e., $\gamma_{\epsilon,s} \sim \Gamma(M, \lambda_s / (1 + \epsilon_s))$. Also, we can model $\gamma_{\epsilon,k}$, which is the instantaneous received SNR at the kth neighboring BS after MRC, as a gamma distributed r.v. with mean $M\lambda_k / (1 + \epsilon_k)$, i.e., $\gamma_{\epsilon,k} \sim \Gamma(M, \lambda_k / (1 + \epsilon_k))$. Thus, the serving BS receives the packet from the source terminal at an average PER given by

$$\mathbb{E}\{\mathsf{PER}(\gamma_{\epsilon,s})\} = 1 - \exp\left(-\frac{\gamma_t(1 + \epsilon_s)}{\lambda_s}\right)$$
$$\sum_{m=0}^{M-1} \frac{1}{m!} \left(\frac{\gamma_t(1 + \epsilon_s)}{\lambda_s}\right)^m \left[1 - \frac{1}{\left(1 + \frac{g\lambda_s}{1+\epsilon_s}\right)^{M-m}}\right] \tag{53}$$

where

$$\mathbb{E}\{(\mathsf{PER}(\gamma_{\epsilon,s}))^2\} = 1 - \exp\left(-\frac{\gamma_t(1 + \epsilon_s)}{\lambda_s}\right)$$
$$\sum_{m=0}^{M-1} \frac{1}{m!} \left(\frac{\gamma_t(1 + \epsilon_s)}{\lambda_s}\right)^m \left[1 - \frac{1}{\left(1 + \frac{2g\lambda_s}{1+\epsilon_s}\right)^{M-m}}\right] \tag{54}$$

and the kth neighboring BS receives the packet from the source terminal at an average PER given by

$$\mathbb{E}\{\mathsf{PER}(\gamma_{\epsilon,k})\} = 1 - \exp\left(-\frac{\gamma_t(1 + \epsilon_k)}{\lambda_k}\right) \sum_{m=0}^{M-1} \frac{1}{m!}$$
$$\left(\frac{\gamma_t(1 + \epsilon_k)}{\lambda_k}\right)^m \left[1 - \frac{1}{\left(1 + \frac{g\lambda_k}{1+\epsilon_k}\right)^{M-m}}\right]. \tag{55}$$

Using (54) and (55), we can derive the average PER of protocol II under imperfect CSI as follows:

$$\overline{\mathsf{PER}}_\epsilon^{(\mathrm{II})}$$
$$= \mathbb{E}\left\{\mathsf{PER}_\epsilon^{(\mathrm{II})}(\gamma_{\epsilon,s}, \gamma_{\epsilon,1}, \ldots, \gamma_{\epsilon,K}, \gamma_{b,1}, \ldots, \gamma_{b,K})\right\}$$
$$= \mathbb{E}\left\{(\mathsf{PER}(\gamma_{\epsilon,s}))^2\right\} \sum_{|\mathcal{K}_c|=0}^{K} \sum_{\mathcal{K}_c} \left\{\prod_{k \in \mathcal{K}_c} (1 - \right.$$
$$\mathbb{E}\{\mathsf{PER}(\gamma_{\epsilon,k})\}) \mathsf{PER}(\gamma_{b,k}) \prod_{k' \in \mathcal{K} \backslash \mathcal{K}_c} \mathbb{E}\{\mathsf{PER}(\gamma_{\epsilon,k'})\}\left.\right\}$$
$$= \left(1 - \exp\left(-\frac{\gamma_t(1 + \epsilon_s)}{\lambda_s}\right) \sum_{m=0}^{M-1} \frac{1}{m!} \left(\frac{\gamma_t(1 + \epsilon_s)}{\lambda_s}\right)^m\right.$$
$$\left.\left[1 - \frac{1}{\left(1 + \frac{2g\lambda_s}{1+\epsilon_s}\right)^{M-m}}\right]\right) \sum_{|\mathcal{K}_c|=0}^{K} \sum_{\mathcal{K}_c} \left\{\prod_{k \in \mathcal{K}_c}\right.$$
$$\exp\left(-\frac{\gamma_t(1 + \epsilon_k)}{\lambda_k}\right) \sum_{m=0}^{M-1} \frac{1}{m!} \left(\frac{\gamma_t(1 + \epsilon_k)}{\lambda_k}\right)^m \left[1 - \right.$$
$$\left.\frac{1}{\left(1 + \frac{g\lambda_k}{1+\epsilon_k}\right)^{M-m}}\right] \mathsf{PER}(\gamma_{b,k}) \prod_{k' \in \mathcal{K} \backslash \mathcal{K}_c} (1 - $$
$$\exp\left(-\frac{\gamma_t(1 + \epsilon_{k'})}{\lambda_{k'}}\right) \sum_{m=0}^{M-1} \frac{1}{m!} \left(\frac{\gamma_t(1 + \epsilon_{k'})}{\lambda_{k'}}\right)^m$$
$$\left.\left[1 - \frac{1}{\left(1 + \frac{g\lambda_{k'}}{1+\epsilon_{k'}}\right)^{M-m}}\right]\right)\right\}. \tag{56}$$

6. Numerical Results

Throughout this section, the selected transmission scheme is uncoded BPSK, i.e., $\alpha = 67.7328$, $g = 0.9819$, $\gamma_t = 4.2935$ [35]. First, we consider symmetric topology corresponding to the situation when the source terminal is located near the cell edge. In this case, the average received SNRs from the
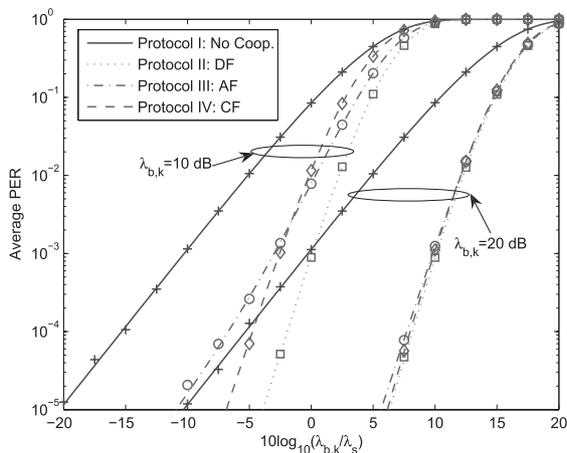
Fig. 5 Average PER of cooperative multicell ARQ protocols when $K = 2$, $M = 2$ for symmetric multicell network. The markers '+', 'square', 'circle', and 'diamond' denote the monte carlo results of protocols I, II, III, and IV, respectively.

Fig. 6 Average PER of cooperative multicell ARQ protocols when $M = 2$ and $\lambda_s = 10\,\mathrm{dB}$ for symmetric multicell network.

source terminal at the serving BS λ_s and at all the neighboring BSs λ_k are equal, and the average received SNRs of the backhaul links $\lambda_{b,k}$ are equal for all k. For protocol IV, the rate R_k of the backhaul link is set at $\log_2(1 + \gamma_{b,k})$. For convenience, we refer to the average received SNR from the source terminal at a BS as the main link SNR, and refer to the average received SNR of the backhaul link as the backhaul link SNR.

First, we verify the derived average PER expressions in Sect. 3 with Monte Carlo simulation results for $K = 2$ and $M = 2$ in Fig. 5. We consider $\lambda_{b,k} = 10\,\mathrm{dB}$ and $20\,\mathrm{dB}$ for all k and vary λ_s. The instantaneous SNR of all links are randomized for each simulated realization. It can be seen that the analytical and simulation results match very well. Compared to the conventional ARQ protocol, we observe that all cooperative multicell ARQ protocols provide much lower average PER. Moreover, the performance gap between each cooperative multicell ARQ protocol reduces as the SNR of the backhaul link increases.

Next, we compare the effect of the number of neighboring BSs and the number of receiver antennas at each BS for $\lambda_s = 10\,\mathrm{dB}$ in Figs. 6 and 7, respectively. In Fig. 6, we set $M = 2$ and compare the scenario when $K = 2$ and 5. It can be observed that there are crossing points between the cooperative multicell protocols. When the backhaul link is the performance bottleneck, protocol III outperforms the other two protocols. Yet, the chance that the backhaul link has lower quality than the main link is rare in practice. All three protocols start to converge to the same error floor as the SNR of the backhaul becomes large, but protocol II reaches the error floor at a rate much faster than the other two protocols. Although the backhaul links become more & more reliable, the main link still remains unreliable and becomes the bottleneck that leads to the error floor. In addition, the performances of all cooperative protocols improve as the number of neighboring BSs increases. Similar behavior can also be seen in Fig. 7 where the employment of multiple antennas at
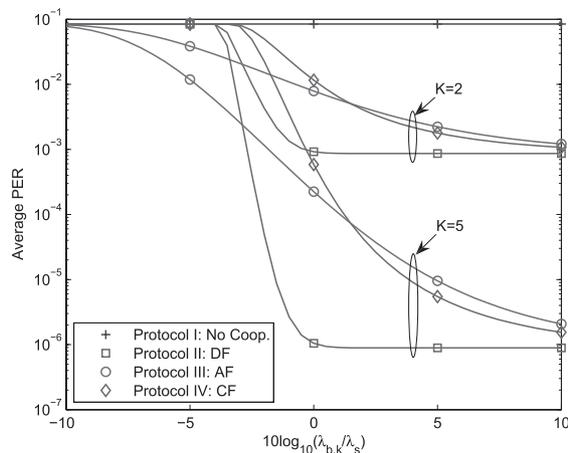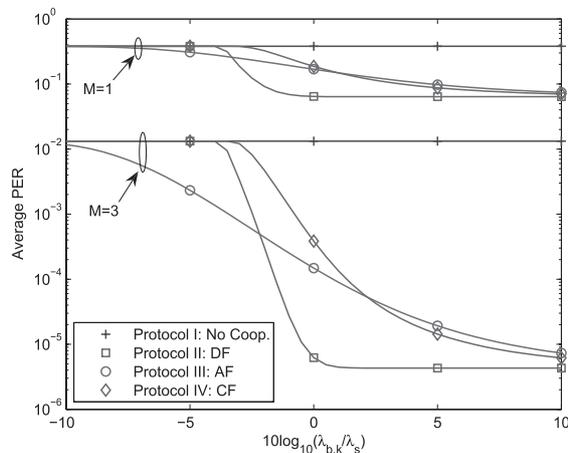

Fig. 7 Average PER of cooperative multicell ARQ protocols when $K = 2$ and $\lambda_s = 10\,\mathrm{dB}$ for symmetric multicell network.

each BS improves the reliability significantly.

In Fig. 8, we consider the effect of imperfect CSI estimation at BSs as described in Sect. 4, by letting ϵ_k set at ϵ for every $k \in \mathcal{K}$ and $\epsilon = 0.1, 0.4, 0.8$. It can be observed that imperfect CSI increases the error floor of protocol II, but hardly moves the waterfall regime. This is because the average PER is dominated by the error from the backhaul links before the waterfall. After the waterfall, the average PER is dominated by the error from the main links, which are affected from the imperfect CSI.

Figure 9 shows the effect of asymmetric network topology on the performance of the cooperative multicell ARQ protocols. Here, the asymmetry is introduced by setting the average SNR between the source terminal and each neighboring BS lower than that between the source terminal and the serving BS with a factor ρ, namely, $\gamma_k = \rho \gamma_s$ for any $k \in \mathcal{K}$. The asymmetry does not change the performance behavior of the protocols but changes the error floor and the waterfall point. The error floor is higher and stronger backhaul links are required to make the average PER converge to
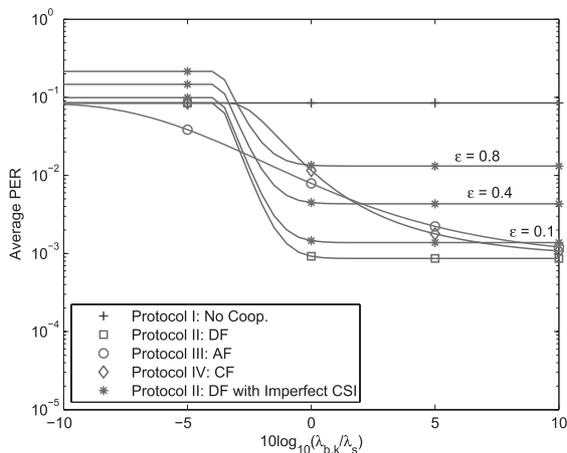
Fig. 8 Average PER of cooperative multicell ARQ protocols when $K = 2$, $M = 2$, and $\lambda_s = 10\,\mathrm{dB}$ for symmetric multicell network. The effect of imperfect CSI on the decoding error for ODF is reflected by setting different ϵ.
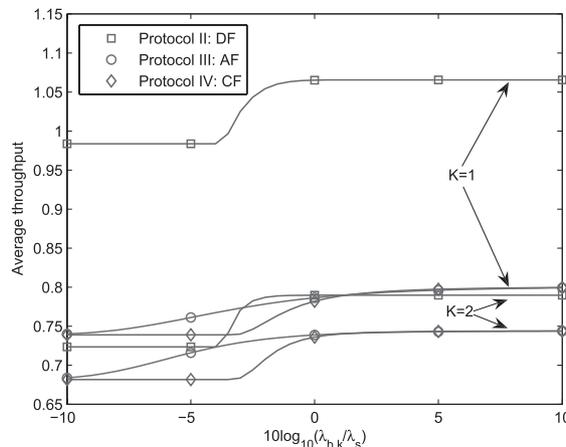

Fig. 10 Average throughput of cooperative multicell ARQ protocols when $M = 2$ and $\lambda_s = 10\,\mathrm{dB}$ for symmetric multicell network.

7. Conclusion

In this paper, we proposed several cooperative multicell ARQ protocols via backhaul links to improve both reliability and throughput for uplink MIMO channels. We considered three types of multicell processing, namely, DF, AF, and CF. For each scheme, we derived the average PER and throughput. In addition, we studied the effect of imperfect CSI on DF. Numerical results showed that the proposed cooperative multicell ARQ protocols can significantly reduce the average PER compared to conventional ARQ protocol. The degree of improvement depends on the type of multicell processing, the operating average SNR, number of receiver antennas, and number of neighboring BSs. Among the proposed protocols, the protocol with DF processing is most promising in terms of average PER, throughput, and backhaul capacity requirement. However, the latency requirement on backhaul links for DF processing is more stringent compared to AF and CF processing. Therefore, a careful comparison of the backhaul link latency and capacity requirements for practical deployment is required for choosing the most appropriate multicell ARQ protocol. There are many revenues for future work. One possible extension is to consider the possibility of selective processing in both AF and CF cases in order to reduce the amount of backhaul traffic. Furthermore, this work only considers uplink channels and the extension of these cooperative multicell ARQ protocols for downlink channels may be interesting to explore.
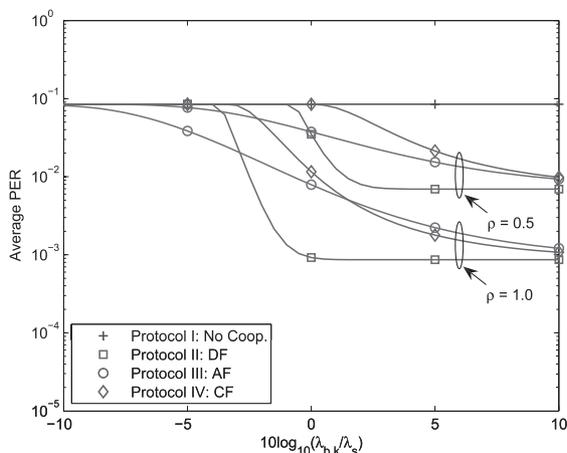
Fig. 9 Average PER of cooperative multicell ARQ protocols when $K = 2$, $M = 2$, and $\lambda_s = 10\,\mathrm{dB}$, comparing the symmetric topology ($\rho = 1.0$) and the asymmetric topology ($\rho = 0.5$) when $\lambda_k = \rho\lambda_s$ for all k.

the error floor.

Lastly, the average throughput of the cooperative multicell ARQ protocols are compared in Fig. 10 for $\lambda_s = 10\,\mathrm{dB}$, $R = 1$, $b = 1$, $L = 1080$, $C = 32$, and $K = 1$ or 2. It can be seen that protocol II has a higher throughput compared to other protocols, especially in the regime with good backhaul link. This is because the neighboring BSs in protocol II selectively retransmit the packet. When the backhaul link SNR is very high, protocols III and IV provide the same average throughput. From Fig. 6, we see that protocols III and IV have similar average PERs and since both protocols always employ all the backhaul transmissions, they will lead to the same average throughput. By increasing $K = 1$ to $K = 2$, we observe a decrease in the average throughput due to the presence of more backhaul transmissions. This is due to the fact that we have defined the average number of transmissions in (39) to include both wireless and backhaul transmissions.

References

[1] M. Sawahashi, Y. Kishiyama, A. Morimoto, D. Nishikawa, and M. Tanno, "Coordinated multipoint transmission/reception techniques for LTE-advanced," IEEE Wireless Commun. Mag., vol.17, no.3, pp.26–34, June 2010.

[2] K. Safjan, V. D'Amico, D. Bültmann, D. Martín-Sacristán, A. Saadani, and H. Schöneich, "Assessing 3GPP LTE-advanced as IMT-advanced technology: The WINNER+ evaluation group approach," IEEE Commun. Mag., vol.49, no.2, pp.92–100, Feb. 2011.

[3] R. Irmer, H. Droste, P. Marsch, M. Grieger, G. Fettweis, S. Brueck, H.P. Mayer, L. Thiele, and V. Jungnickel, "Coordinated multipoint: Concepts, performance, and field trial results," IEEE Commun. Mag., vol.49, no.2, pp.102–111, Feb. 2011.

[4] I.F. Akyildiz, D.M. Gutierrez-Estevez, and E.C. Reyes, "The evolution to 4G cellular systems: LTE-advanced," Physical Commun., vol.3, no.4, pp.217–244, 2010.

[5] D. Gesbert, S. Hanly, H. Huang, S. Shamai, O. Simeone, and W. Yu, "Multi-cell MIMO cooperative networks: A new look at interference," IEEE J. Sel. Areas Commun., vol.28, no.9, pp.1380–1408, Sept. 2010.

[6] W.W.L. Ho, T.Q.S. Quek, S. Sun, and R.W. Heath, "Decentralized precoding for multicell MIMO downlink," IEEE Trans. Wireless Commun., vol.10, no.6, pp.1798–1809, June 2011.

[7] D.W.H. Cai, T.Q.S. Quek, and C.W. Tan, "Coordinated max-min SIR optimization in multicell downlink — Duality and algorithm," Proc. IEEE Int. Conf. on Commun., pp.1–6, Kyoto, Japan, June 2011.

[8] D.W.H. Cai, T.Q.S. Quek, C.W. Tan, and S. Low, "Max-min weighted SIR in coordinated multicell MIMO downlink," Proc. IEEE Int. Symp. of Modeling and Optimization of Mobile, Ad Hoc, and Wireless Networks, pp.286–293, Princeton, NJ, May 2011.

[9] D.W.H. Cai, T.Q.S. Quek, C.W. Tan, and S. Low, "Max-min SINR optimization in coordinated multicell downlink — Duality and algorithms," IEEE Trans. Signal Process., 2011, submitted.

[10] O. Simeone, O. Somekh, H.V. Poor, and S. Shamai, "Local base station cooperation via finite-capacity links for the uplink of linear cellular networks," IEEE Trans. Inf. Theory, vol.55, no.1, pp.190–204, Jan. 2009.

[11] A. Sanderovich, O. Somekh, H.V. Poor, and S. Shamai, "Uplink macro diversity of limited backhaul cellular network," IEEE Trans. Inf. Theory, vol.55, no.8, pp.3457–3478, Aug. 2009.

[12] O. Somekh, B.M. Zaidel, and S. Shamai, "Sum rate characterization of joint multiple cell-site processing," IEEE Trans. Inf. Theory, vol.53, no.12, pp.4473–4497, Dec. 2007.

[13] T.Q.S. Quek, D. Dardari, and M.Z. Win, "Energy efficiency of dense wireless sensor networks: To cooperate or not to cooperate," IEEE J. Sel. Areas Commun., vol.25, no.2, pp.459–470, Feb. 2007.

[14] T.Q.S. Quek, H. Shin, and M.Z. Win, "Robust wireless relay networks: Slow power allocation with guaranteed QoS," IEEE J. Sel. Top. Signal Process., vol.1, no.4, pp.700–713, Dec. 2007.

[15] A. Bletsas, H. Shin, and M.Z. Win, "Outage analysis for cooperative communication with multiple amplify-and-forward relays," Electron. Lett., vol.43, no.6, pp.51–52, March 2007.

[16] A. Bletsas, H. Shin, and M.Z. Win, "Outage optimality of opportunistic amplify-and-forward relaying," IEEE Commun. Lett., vol.11, no.3, pp.261–263, March 2007.

[17] A. Bletsas, H. Shin, and M.Z. Win, "Cooperative communications with outage-optimal opportunistic relaying," IEEE Trans. Wireless Commun., vol.6, no.9, pp.3450–3460, Sept. 2007.

[18] H. Shin and J.B. Song, "MRC analysis of cooperative diversity with fixed-gain relays in Nakagami-m fading channels," IEEE Trans. Wireless Commun., vol.7, no.6, pp.2069–2074, June 2008.

[19] B. Barua, H.Q. Ngo, and H. Shin, "On the SEP of cooperative diversity with opportunistic relaying," IEEE Commun. Lett., vol.12, no.10, pp.727–729, Oct. 2008.

[20] H.Q. Ngo, T.Q.S. Quek, and H. Shin, "Random coding error exponent for dual-hop Nakagami-m fading channels with amplify-and-forward relaying," IEEE Commun. Lett., vol.13, no.11, pp.823–825, Nov. 2009.

[21] Y. Song, H. Shin, and E.K. Hong, "MIMO cooperative diversity with scalar-gain amplify-and-forward relaying," IEEE Trans. Commun., vol.57, no.7, pp.1932–1938, July 2009.

[22] T.Q.S. Quek and H. Shin, "Bursty relay networks in the low-SNR regimes," IEEE Trans. Commun., vol.58, no.2, pp.694–705, Feb. 2010.

[23] T.Q.S. Quek, M.Z. Win, and M. Chiani, "Robust power allocation algorithms for wireless relay networks," IEEE Trans. Commun., vol.58, no.7, pp.1931–1938, July 2010.

[24] H.Q. Ngo, T.Q.S. Quek, and H. Shin, "Amplify-and-forward two-way relay networks: Error exponents and resource allocation," IEEE Trans. Commun., vol.58, no.9, pp.2653–2666, Sept. 2010.

[25] T. Sethakaset, T.Q.S. Quek, and S. Sun, "Joint source-channel optimization for wireless relay networks," IEEE Trans. Commun., vol.59, no.4, pp.1114–1122, April 2011.

[26] R. Kudo, Y. Takatori, K. Nishimori, A. Ohta, and S. Kubota, "New downlink beamforming method for cooperative multiple access point systems," IEICE Trans. Commun., vol.E90-B, no.9, pp.2303–2311, Sept. 2007.

[27] J. Hu and N. Beaulieu, "Closed-form expressions for the outage and error probabilities of decode-and-forward relaying in dissimilar Rayleigh fading channels," Proc. IEEE Int. Conf. on Commun., pp.5553–5557, Glasgow, Scotland, June 2007.

[28] K. Teshima, K. Yamamoto, H. Murata, and S. Yoshida, "Capacity analysis of cooperative relaying networks with adaptive relaying scheme selection," IEICE Trans. Commun., vol.E92-B, no.12, pp.3744–3752, Dec. 2009.

[29] K. Woradit, T.Q.S. Quek, W. Suwansantisuk, H. Wymeersch, L. Wuttisittikulkij, and M.Z. Win, "Outage behavior of selective relaying schemes," IEEE Trans. Wireless Commun., vol.8, no.8, pp.3890–3895, Aug. 2009.

[30] Asaduzzaman and H.Y. Kong, "Code combining in cooperative communication," IEICE Trans. Commun., vol.E91-B, no.3, pp.805–813, March 2008.

[31] K. Lee and L. Hanzo, "Resource-efficient wireless relaying protocols," IEEE Wireless Commun. Mag., vol.17, no.2, pp.66–72, April 2010.

[32] P. Liu, Z. Tao, Z. Lin, E. Erkip, and S. Panwar, "Cooperative wireless communications: A cross-layer approach," IEEE Wireless Commun. Mag., vol.13, no.4, pp.84–92, Aug. 2006.

[33] D. Soldani and S. Dixit, "Wireless relays for broadband access," IEEE Commun. Mag., vol.46, no.3, pp.58–66, March 2008.

[34] E. Malkamaki and H. Leib, "Performance of truncated type-II hybrid ARQ schemes with noisy feedback over block fading channels," IEEE Trans. Commun., vol.48, no.9, pp.1477–1487, Sept. 2000.

[35] Q. Liu, S. Zhou, and G.B. Giannakis, "Cross-layer combining of adaptive modulation and coding with truncated ARQ over wireless links," IEEE Trans. Wireless Commun., vol.3, no.5, pp.1746–1755, Sept. 2004.

[36] V. Mahinthan, H. Rutagemwa, J.W. Mark, and X.S. Shen, "Cross-layer performance study of cooperative diversity system with ARQ," IEEE Trans. Veh. Technol., vol.58, no.2, pp.705–719, Feb. 2009.

[37] B. Zhao and M.C. Valenti, "Practical relay networks: A generalization of hybrid-ARQ," IEEE J. Sel. Areas Commun., vol.23, no.1, pp.7–18, Jan. 2005.

[38] L. Dai and K. Letaief, "Throughput maximization of ad-hoc wireless networks using adaptive cooperative diversity and truncated ARQ," IEEE Trans. Commun., vol.56, no.11, pp.1907–1918, Nov. 2008.

[39] S. Lee, W. Su, S. Batalama, and J. Matyjas, "Cooperative decode-and-forward ARQ relaying: Performance analysis and power optimization," IEEE Trans. Wireless Commun., vol.9, no.8, pp.2632–2642, Aug. 2010.

[40] K. Woradit, T.Q.S. Quek, and Z. Lei, "Cooperative multicell ARQ in

MIMO cellular systems," Proc. IEEE Int. Workshop on Signal Processing Adv. in Wireless Commun., pp.1–5, Marrakech, Morocco, June 2010.

[41] K. Woradit, T.Q.S. Quek, and Z. Lei, "Cooperative multicell ARQ — Packet error rate and throughput analysis," Proc. IEEE Wireless Commun. Networking Conf., pp.1–6, Sydney, Australia, April 2010.

[42] M. Kuhn, J. Wagner, and A. Wittneben, "Cooperative processing for the WLAN uplink," Proc. IEEE Wireless Commun. Networking Conf., pp.1294–1299, Las Vegas, NV, March 2008.

[43] E. Yilmaz, R. Knopp, and D. Gesbert, "Some systems aspects regarding compressive relaying with wireless infrastructure links," Proc. IEEE Global Telecomm. Conf., pp.1–5, New Orleans, LO, Dec. 2008.

[44] M. Abramowitz and I.A. Stegun, Handbook of Mathematical Functions with Formulas, Graphs, and Mathematical Tables, 10th ed., Dover Publications, New York, 1972.

[45] M.H. DeGroot and M.J. Schervish, Probability and Statistics, 3rd ed., Addison-Wesley, Boston, 2002.

[46] L. Cao, P.Y. Kam, and M. Tao, "Impact of imperfect channel state information on ARQ schemes over Rayleigh fading channels," Proc. IEEE Int. Conf. on Commun., pp.1–5, Dresden, Germany, June 2009.

[47] S. Haykin, Adaptive Filter Theory, 4th ed., Prentice-Hall, Upper Saddle River, New Jersey, 2002.

[48] P.Y. Kam, "Optimal detection of digital data over the nonselective Rayleigh fading channel with diversity reception," IEEE Trans. Commun., vol.39, no.2, pp.214–219, Feb. 1991.

Tony Q. S. Quek received the B.E. and M.E. degrees in Electrical and Electronics Engineering from Tokyo Institute of Technology, Tokyo, Japan, in 1998 and 2000, respectively. At Massachusetts Institute of Technology (MIT), Cambridge, MA, he earned the Ph.D. in Electrical Engineering and Computer Science in Feb. 2008. Since 2008, he has been with the Institute for Infocomm Research, A*STAR, where he is currently a Principal Investigator and Scientist. His main research interests are the application of mathematical, optimization, and statistical theories to communication, detection, signal processing, information theoretic and resource allocation problems. Specific current research topics include cooperative networks, interference networks, heterogeneous networks, green communications, wireless security, smart grid, and cognitive radio. Dr. Quek has been actively involved in organizing and chairing sessions, and has served as a member of the Technical Program Committee (TPC) in a number of international conferences. He served as the Technical Program Chair for the Services & Applications Track for the IEEE Wireless Communications and Networking Conference (WCNC) in 2009, the Cognitive Radio & Cooperative Communications Track for the IEEE Vehicular Technology Conference (VTC) in Spring 2011, and the Wireless Communications Symposium for the IEEE Globecom in 2011; as Technical Program Vice-Chair for the IEEE Conference on Ultra Wideband in 2011; and as the Workshop Chair for the IEEE Globecom 2010 Workshop on Femtocell Networks and the IEEE ICC 2011 Workshop on Heterogeneous Networks. Dr. Quek is currently an Editor for the Wiley Journal on Security and Communication Networks, the European Transactions on Telecommunications, and the IEEE Wireless Communications Letters. He was Guest Editor for the Journal of Communications and Networks (Special Issue on Heterogeneous Networks) in 2011. Dr. Quek received the Singapore Government Scholarship in 1993, Tokyu Foundation Fellowship in 1998, and the A*STAR National Science Scholarship in 2002. He was honored with the 2008 Philip Yeo Prize for Outstanding Achievement in Research, the IEEE Globecom 2010 Best Paper Award, and the 2011 JSPS Invited Fellow for Research in Japan.

Kampol Woradit received the B.Eng. degree in Electrical Engineering from Chulalongkorn University, Thailand, in 2002, and the Ph.D. degree in Electrical Engineering from the same university, in 2010. From 2007 to 2008, he was a visiting student at the Laboratory for Information and Decision Systems (LIDS), Massachusetts Institute of Technology (MIT), Cambridge, MA, USA. In 2009, he was on a postgraduate research attachment at the Institute for Infocomm Research, A*STAR. In 2010, he joined Srinakharinwirot University, Thailand, where he is now a faculty member at the Department of Electrical Engineering. His research interests include wireless communications, WDM network protection, and channel coding. Dr. Woradit received the Royal Golden Jubilee Scholarships from the Thailand Research Fund for his Ph.D. program. He received the NEWCOM++ Best Paper Award 2011. He served as a member of the Technical Program Committee (TPC) for the IEEE VTC in Spring 2011.

Hyundong Shin received the B.S. degree in Electronics Engineering from Kyung Hee University, Korea, in 1999, and the M.S. and Ph.D. degrees in Electrical Engineering from Seoul National University, Korea, in 2001 and 2004, respectively. From 2004 to 2006, Dr. Shin was a Postdoctoral Associate at the Laboratory for Information and Decision Systems (LIDS), Massachusetts Institute of Technology (MIT), Cambridge, MA, USA. In 2006, he joined Kyung Hee University, Korea, where he is now an Assistant Professor at the Department of Electronics and Radio Engineering. His research interests include wireless communications and information theory with current emphasis on MIMO systems, cooperative and cognitive communications, network interference, vehicular communication networks, intrinsically secure networks, and quantum information science. Dr. Shin has served as a Member of the Technical Program Committee (TPC) in a number of international conferences. He served as the Technical Program Co-chair for the PHY Track of the IEEE Wireless Communications and Networking Conference (WCNC) in 2009 and the Communication Theory Symposium of the IEEE Global Communications Conference (Globecom) in 2012. He is currently an Editor for the IEEE Transactions on Wireless Communications and the KSII Transactions on Internet and Information Systems. He was a Guest Editor for the EURASIP Journal on Advances in Signal Processing (Special Issue on Wireless Cooperative Networks) in 2008. Dr. Shin was honored with the Knowledge Creation Award in the field of Computer Science from Korean Ministry of Education, Science and Technology (2010). He received the IEEE Communications Society's Guglielmo Marconi Prize Paper Award (2008), the IEEE VTC Best Paper Award (2008 Spring), and the IEEE VTS APWCS Best Paper Award (2010).

Zander (Zhongding) Lei received his B.S. (Honor) and the Ph.D. degrees from Beijing Jiaotong University, Beijing, China in 1991 and 1997, and the M.Eng degree from Tong Ji University, Shanghai, China in 1994. From 1997 to 1999, he was a Post-doctoral Fellow in the National University of Singapore. Since 1999, he has been with Institute for Infocomm Research Singapore, where he is a Project Manager and Senior Scientist, leading a team working on 3GPP LTE-Advanced standard. He is a technical leader in IEEE 802.22 standard for wireless regional area network (WRAN) standardizing the first cognitive radio system. His research interests include next generation/emerging wireless communication systems/technologies, cooperative communications, cognitive radio etc. He has 9 patents granted and has published over 90 papers in international refereed journals or conferences. Dr. Lei is a co-recipient of Institution Engineering of Singapore Prestigious Engineering Achievement Awards in both 2005 and 2007. He has been the PHY Technical Editor for IEEE 802.22 standard since 2006. He has served as Co-Chairs/Panel Chairs and in Technical Program Committee for various IEEE international conferences on wireless communications.