Interference Management in Femtocell Networks with Hybrid-ARQ and Interference Cancellation

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***Abstract*—Femtocells are small cellular base stations targeting in-home usage and deployed by end-users. Because of the unplanned nature of their deployment, they can suffer from severe inter-cell interference with neighboring femtocells in dense deployments. In addition, coordination is hardly feasible due to delays induced by the backhaul infrastructure of these home femtocell networks. We propose a novel and decentralized interference mitigation scheme that combines hybrid-ARQ and incremental redundancy with an interference cancellation decoder. Our performance evaluation based on analytical modeling and Monte Carlo experiments shows that our scheme is effective at combating interference without requiring any coordination.**

I. Introduction

The current and growing expansion need of cellular networks represents a challenge as laying out and deploying new infrastructure is extremely expensive. Femtocells are believed to be a cost effective solution to expand the coverage and capacity of 3G and beyond networks [1].

Femtocells are small and low-power cellular base stations used outdoor to enhance coverage, or indoor for enterprise or in-home usage. In the case of in-home usage, they are deployed by end-users and connected to the operator network by a digital subscriber line (DSL), cable modem or optical fiber connection [2].

End-user deployments are typically unplanned and can suffer from severe inter-cell interference with neighboring femtocells in dense deployments [3], [4], [5]. Because femtocells are not directly connected to the operator backhaul network, coordination between femtocells for resource management is hardly feasible.

The 3rd Generation Partnership Project (3GPP) Long Term Evolution (LTE) [6] has chosen orthogonal frequency division multiple access (OFDMA) technology for multiplexing on the downlink. OFDMA ensures orthogonality of the subcarriers and therefore, there is no intra-cell interference. However, interference can be experienced from users in adjacent cells.

In this paper, we concentrate on LTE and LTE-advanced technologies (so-called 4G) with OFDMA physical layers and explore alternative strategies to mitigate interference.

In LTE, hybrid automatic retransmission request (hybrid-ARQ) is used to reduce errors in transmissions by retransmitting and combining the information when a frame is received with errors [7]. With incremental redundancy, additional and new redundancy information is transmitted and combined with information already transmitted offering a coding gain. A frame is retransmitted until it is discarded or a maximum number of retransmissions is reached. From an information-theoretic perspective, mutual information is accumulated over retransmissions, increasing the probability to decode [8].

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The throughput of hybrid-ARQ has been investigated for Gaussian input signals [8] over a Gaussian channel with fading and in [9], rate adaptation is performed to maintain a fixed outage probability. In [10] the diversity-multiplexing-delay tradeoff has been studied for the multiple-input multiple-output (MIMO) ARQ channel.

Our work differs from prior work because we take advantage of the non-Gaussian nature of interference in home femtocell deployments where there are typically only one or two strong dominant interferers [11]. We consider signals coming from discrete alphabets in order to be able to benefit from the structure of the interference. Gaussian signals achieve the maximum spectral efficiency. However, practical systems make use of small, finite-size input alphabets.

Under these assumptions, we propose a novel and decentralized strategy that combines interference cancellation decoding [12] with an incremental redundancy hybrid-ARQ policy [8].

To evaluate the performance of this strategy, we develop an analytical model of the throughput achieved by an hybrid-ARQ protocol with an interference cancellation decoder. In particular, our model builds on an information-theoretic characterization of the achievable rate with interference cancellation.

Our results show that our scheme is effective at combating interference without requiring any coordination. However, perfect channel state information (CSI) is assumed at the receiver.

In the remainder of this paper, we describe our system model and assumptions in Section II, briefly describe our model in Section III and give our simulation results in Section IV. Finally, we give some concluding remarks in Section V.

II. System Model and Assumptions

We focus on a downlink scenario. Without loss of generality, we currently consider single antenna transmission. Furthermore, transmissions are slotted and perfectly synchronized.

We have N transmitters, where node 0 is the transmitter of interest and the remaining $N-1$ transmitters are interferers. We let d_k be the distance between the node k and the receiver. 4G systems are based on OFDMA physical layer [13]. We let $y[m]_i$ be the received signal in resource block i at time m. In LTE, every resource block is defined as a group of M subcarriers. Within a given cell, we assume that resource blocks are orthogonal to each other. Hence, we can write the received signal $y[m]_i$ at time m as

$$y[m]_i = \sum_{j=0}^{M-1} \sum_{k=0}^{N-1} \sqrt{P_k d_k^{-\alpha}} h_k[m,i,j] \beta[m]_k x_k[m,i,j] + z[m,i,j]. \quad (1)$$

where $x_k[m,i,j]$ is the transmitted signal from node k in subcarrier j of resource block i, $\beta_m[k]$ is a so-called *activity factor*, $z[m,i,j]$ is thermal noise, P_k is the transmission power, α is the path loss exponent and $h_k[m,i,j]$ is the channel coefficient. We model $z[m,i,j]$ as an independently and identically distributed (iid) zero-mean additive white Gaussian noise (AWGN) process with variance σ^2. If we concentrate on a particular subcarrier, the received signal in the nth subcarrier at time m is

$$y[m,n] = \sum_{k=0}^{N-1} \sqrt{P_k d_k^{-\alpha}} h_k[m,n] \beta_k x_k[m,n] + z[m,n] \quad (2)$$

The random variable $h_k[m,n]$ is iid for each slot with a Rayleigh distribution. Hence, the channel coefficient remains constant during the duration of a slot. The activity factor models the traffic load and/or discontinuous transmission (DTX) features of LTE systems [13]. We model β_k with an iid Bernoulli distribution with parameter p. These features are taken into account as they have a direct effect on the interference distribution.

The retransmission protocol is an hybrid-ARQ scheme using incremental redundancy [8]. For comparison purpose, we also consider a simple ARQ scheme that retransmits the same data block in case of unsuccessful transmission. The parameter M_{max} is the maximum number of ARQ rounds. Therefore, a given frame can be retransmitted at most M_{max} times and is discarded if M_{max} is reached. We assume perfect CSI of the desired and interference signals at the receiver and we let R define the transmission rate given by a particular modulation and coding scheme (MCS).

III. Average Throughput Analysis of Hybrid-ARQ with Interference Cancellation

Without loss of generality, our analysis can consider a single subcarrier and we can drop the index n from (2). We consider a slotted (i.e. discrete-time) system where each slot corresponds to a frame transmission. We define the following symbols:

- Λ is the average throughput expressed in frames per second.
- $p[m]$ is the probability that a frame is successfully decoded at slot m.

The behavior of our system can be modeled by a discrete-time Markov chain [14]. However, because (1) a new channel coefficient $h_k[m,n]$ is possibly drawn at every slot, and (2) the activity factor can change the number of active sources at every slot, the Markov chain is inhomogeneous i.e. the state transition probabilities can change over time. Remember from Section II that a frame can be retransmitted at most M_{max} times before being discarded. Hence, let X_n be the retransmission state of the source (see Figure 1). The Markov chain X_n has $M_{max}+2$ states (numbered from 0 to $M_{max}+1$): a frame transmission attempt always initiates and finishes in state 0. A frame retransmission corresponds to a transition from state i to $i+1$. A successful frame transmission corresponds to a transition from any state $i = 0, \ldots, M_{max}$ to the state 0. Finally, the frame is dropped if state $M_{max}+1$ is reached. The transition probabilities are the following:

$$\begin{aligned} &p_X(i,i+1) = 1 - p[m+i] = q[m+i], \quad && i = 0, \ldots, M_{max} \\ &p_X(i,0) = p[m+i], && i = 0, \ldots, M_{max} \\ &p_X(M_{max}+1, 0) = 1 && \end{aligned} \quad (3)$$

where $p_X(i,j) = \mathbb{P}(X_{n+1} = j | X_n = i)$. Each new frame transmission attempt[1] corresponds to a trip on the chain X_n starting in state 0 and returning back to the state 0. The average throughput Λ can be computed by dividing the average number of successful frame transmissions per trip by the average duration of a trip. For a trip from state 0 back to state 0, we can define two random variables:

- N_s is the number of successful frame transmissions per trip. Observe that N_s is equal to 0 or 1.
- T is the duration of a trip.

Now, following the approach in [15], we can write

$$\lambda = \frac{\mathbb{E}^0(N_s)}{\mathbb{E}^0(T)} \quad (4)$$

where $\mathbb{E}^0$ is a Palm expectation [16] (see [15, eq. 9] for a definition specific to the context of (4)). We do not have a

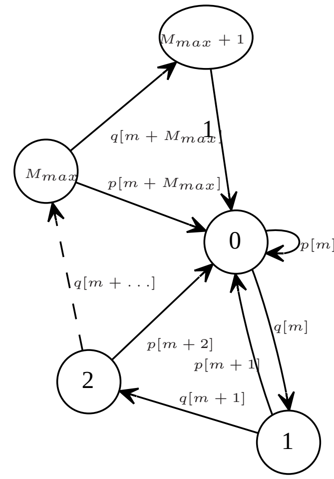


Fig. 1. Retransmission Markov chain X_n: a frame transmission attempt always initiates and finishes in state 0. A frame retransmission corresponds to a transition from state i to $i+1$. A successful frame transmission corresponds to a transition from any state $i = 0, \ldots, M_{max}$ to the state 0. Finally, the frame is dropped if state $M_{max}+1$ is reached. Note that $q[m] = 1 - p[m]$, $\forall m$.

[1]As opposed to a retransmission, which is one transition on the chain.

closed-form expression for $\mathbb{E}^0(N_{\rm s})$ and $\mathbb{E}^0(T)$, but they can be evaluated by simulation. However, we need to be able to compute the transition probability $p[m+i]$ from state i to state 0 at time $m+i$.

We take an information-theoretic approach. Namely, without any interference cancellation, the transition probability is computed as a function of the instantaneous mutual information conditioned on the channel knowledge. For interference cancellation, we follow the mechanism and modeling of [12] and modify the mutual information expression appropriately. Let I_m denote the mutual information between the received and the desired signal at time m and let R denote the target operating rate. In the following, the conditioning on the channel realizations and number of active users is implicitely assumed. For hybrid-ARQ with incremental redundancy, it is shown in [8] that the mutual information is accumulated over retransmissions when incremental redundancy is used. Following [9], we have

$$p[m+i] = \mathbb{P}\left(\sum_{k=m}^{m+i} I_k > R \;\middle|\; \sum_{k=m}^{m+i-1} I_k \right) \tag{5}$$

for $0 < i \leq M_{max}$ and $p[m] = \mathbb{P}\left(I_m > R\right)$, for $i = 0$. For ARQ, we have

$$p[m+i] = \mathbb{P}(I_{m+i} > R) \tag{6}$$

for $0 \leq i \leq M_{max}$. To evaluate equations (5) and (6) we need to compute the mutual information between node 0 and the receiver. To model the effect of interference cancellation, we follow [12]. For a receiver that cancels two interferers, the mutual information is (we ignore the conditioning on the channel for simplicity)

$$\begin{aligned} I(Y;X_0|X_1,X_2) &= \log M_0 \\ &- \frac{1}{M_0 M_1 M_2} \sum_{x_0} \sum_{x_1} \sum_{x_2} \int_y p(y|x_0) \\ &\times \log \frac{\sum_{x_2'} \sum_{x_1'} \sum_{x_0'} p(y|x_0', x_1', x_2')}{\sum_{x_2'} \sum_{x_1'} p(y|x_0, x_1', x_2')} dy. \end{aligned}$$

where Y is the received signal, X_0 is the desired signal, X_1 and X_2 are the interference signals, and M_i, $i = \{0, 1, 2\}$ is the size of the constellation for X_i. If the structure of the interference is known, i.e. the constellation, then the receiver can use it to cancel the interferers. Note the discrete input distribution used to more accurately model practical systems. Also, to take the remaining transmitters with index 3 to $N-1$ into account, we perform a Gaussian approximation. With a receiver that does not cancel interference, we simply compute $I(Y;X_0)$.

To visualize the mutual information with discrete signals, we plot in Figure 2 the CDF of the mutual information for the case when there is no interference and we compare it with the case of canceling two strong interferers. When interference is not taken into account it is clear that higher modulation orders will translate into higher mutual information, but in an scenario with interference, there is not always a clear gain from using higher modulation orders, it will depend on the interference strength.

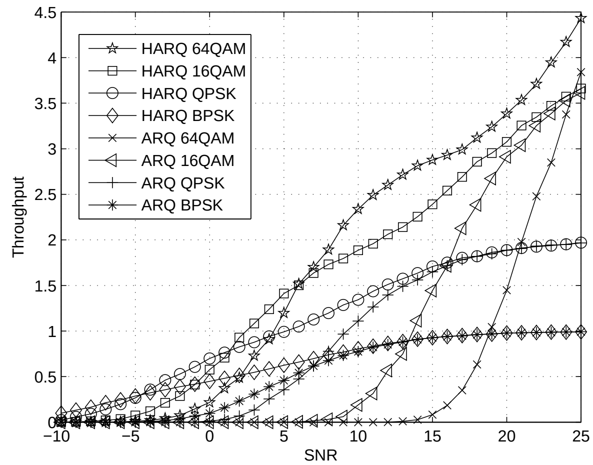


Fig. 3. We consider different modulations, for hybrid-ARQ and ARQ, with $M_{max} = 3$ retransmissions. We show the average throughput for both retransmission protocols and we see the improvement in throughput of hybrid-ARQ over ARQ for all modulations.

IV. Performance Evaluation

In this section, first we give results for a comparison between ARQ and hybrid-ARQ. For a different number of retransmissions, we obtain the throughput with hybrid-ARQ for two cases: without interference and with two strong interferers. Then, we study a Manhattan-like topology when the two strongest interferers can be cancelled. Finally, we evaluate a scenario where interference is randomized by using activity factor. This can be understood as a re-use factor of the network.

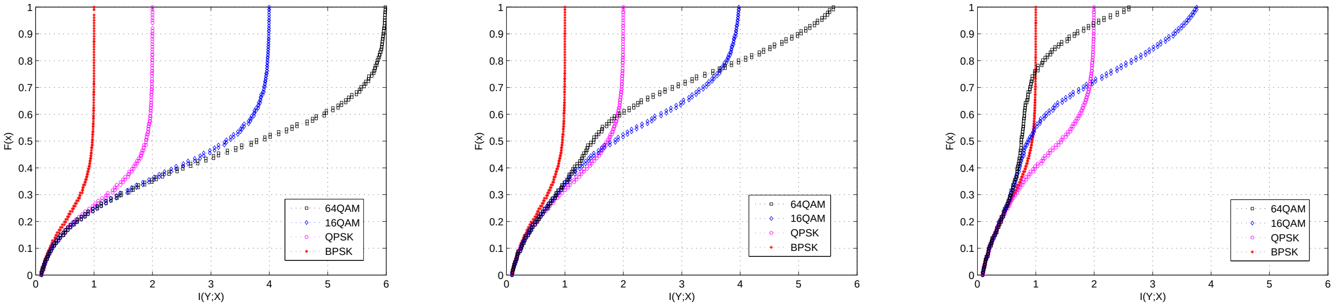
All results are obtained evaluating the throughput expressions in Section III by Monte Carlo experiments averaged over fading and noise distributions. The target rate R remains fixed for each simulation.

Figure 3 compares average throughput the two ARQ protocols. We study a scenario with different modulations (BPSK, QPSK, 16QAM and 64QAM), without interference, and we set M_{max} to 3. The SNR ranges from -10 to 25 dB and the target rate is $R = 2$ bits/second. We clearly observe an improvement in throughput with hybrid-ARQ in comparison with the simple ARQ protocol without combining at the receiver.

We can also see that it is possible to identify SNR intervals for each modulation order and that generally, at high SNR, 64QAM gives the highest throughput.

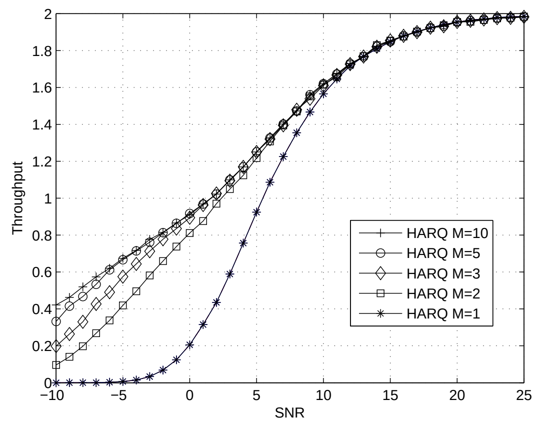
In Figure 4, we plot the average throughput for different values of maximum retransmissions M_{max} (in our terminology, retransmission is equivalent to round) . We focus on QPSK modulation, hybrid-ARQ and $M_{max} = 1, 2, 3, 5, 10$. We consider both no interference and two strong interferers cancellation.

When there is no interference (Figure 4(a)), at most two rounds instead of one gives a gain of around four times at a 0 dB SNR. However, going from two rounds to three rounds gives a gain of only 0.1 in throughput. The later means that just increasing the maximum number of rounds is not sufficient to get a significant gain in throughput. Now,

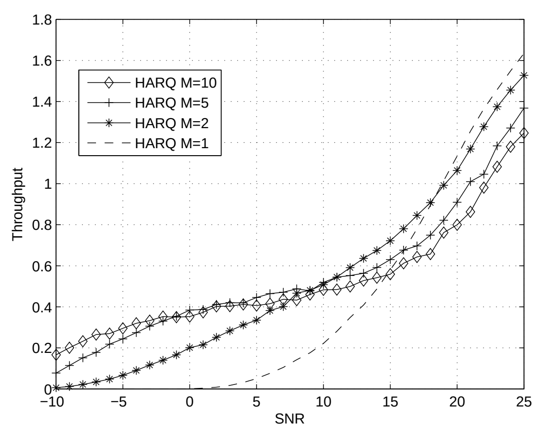


(a) Mutual information CDF. (b) Mutual information CDF, one interferer. (c) Mutual information CDF, two interferers.

Fig. 2. In (a) we have the CDF of the mutual information under Rayleigh fading and without any interference, (b) shows the CDF of the mutual information with one interferer, and (c) for two interferers. The interferers have the same power as the user of interest.



(a) Different number of ARQ rounds without interference



(b) Different number of ARQ rounds with two strong interferers.

Fig. 4. We consider QPSK modulation, for hybrid-ARQ, and we show the average throughput for different numbers of retransmissions $M_{max} = 1, 2, 3, 5, 10$. In (a) we plot the case without any interference and in (b) we see a different trend for the case with two strong interferers, (b) shows that adapting the rate is an optimal way to increase the throughput.

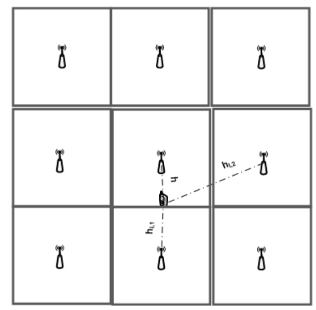


Fig. 5. Manhattan-like topology with the user of interest at the edge of the appartment and the rest of the interfering femtocells placed at the middle of the surrounding appartments

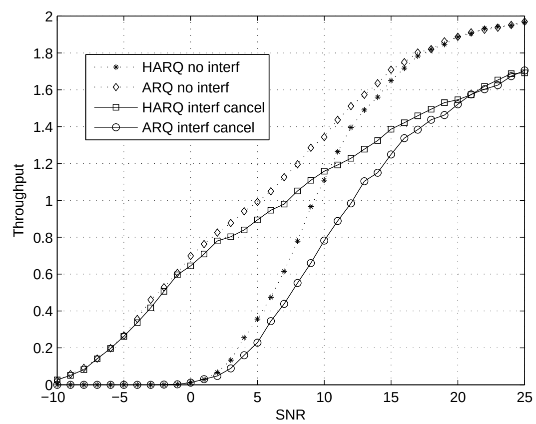


Fig. 6. We look at the scenario in Figure 5 and we consider QPSK modulation, $R = 2$, $M_{max} = 3$ for hybrid-ARQ and ARQ. We show the average throughput with no interference and with interference cancelling two interferers for an SNR from -10 to 25 dB. We do a Gaussian approximation for the interferers that are not cancelled. The SNR without interference cancelling is -7 dB and 6 dB for interference cancellation of the two strongest interferes. The corresponding throughputs are 0.15 and 1, therefore there is a gain of ten times in throughput.

on Figure 4(b) is a scenario with interference. We can observe that in the low SNR region, more retransmission rounds gives the highest throughput, however, at higher SNR, having only one retransmission gives the highest throughput. This is in contradiction of what is expected from having more opportunities to get the information decoded correctly. The reason for this result is that we fix the target rate for each case, which happens when there is no rate adaptation. This behavior suggests that the rate must be adapted depending on the instantaneous SNR.

Next we present our results when combining hybrid-ARQ

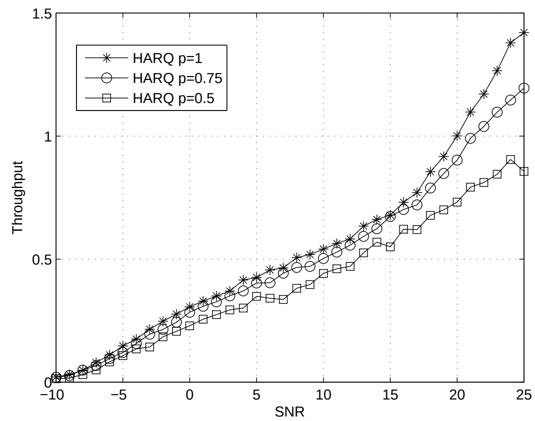


Fig. 7. We consider QPSK modulation, we show the average throughput when the interference is randomized with an activity factor $\beta = 0.5, 0.75$, which means that the interferers will be active either half or 75% of the time and we compare with the case of the interference present all the time. We see that activity factor of 0.5 has the lowest throughput and that activity factor of 75% is closer to the corresponding curve for $\beta = 1$.

with incremental redundancy and interference cancellation of the two strongest interferers. The topology is the Manhattan-like scenario in Figure 5 and is a three by three grid topology, of size 30 by 30 meters, with node 0 in the middle. The receiver is located 5 meters away from the transmitter. This is a typical residential scenario. In Figure 6, we show the results for this topology. We consider QPSK modulation, a target rate of $R = 2$, maximum number of retransmissions $M_{max} = 3$ for both hybrid-ARQ and ARQ. We show the average throughput with and without interference cancellation for an SNR from -10 to 25 dB. For interference cancellation, two interferers can be cancelled. We perform a Gaussian approximation on interferers that are not cancelled. Hence, the SNR without interference cancellation is around -7 dB and the SNR if the two strongest interferers are decoded is around 6 dB. The respective average throughputs are of 0.15 and 1. We observe a gain of around ten times in throughput from cancelling only the two strongest interferers.

Finally, we investigate a bursty interference scenario where the interference is not constant. It is important to investigate how the throughput is affected if we randomize the interference. In femtocell networks, being deployed by end-users, network and frequency planning becomes complicated, since the placement of the femtocells will be unknown for the operator. Moreover, the users may be able to turn them on and off. In our model, if we let the nodes to be either active or inactive, this becomes equivalent to have a re-use factor in the network which creates an interference process tha is no longer ergodic. We investigated the case of interferers being present 50% and 75% of the time, this is equivalent to setting the activity factor $\beta = \{0.5, 0.75\}$ and we compare it against an activity factor $\beta = 1$. There are two interferers. All nodes transmit with unit power for simplicity. The SNR is defined then by $SNR = \frac{1}{N_0+2}$

In Figure 7 we show the curves for activity factors $0.5, 0.75$ and 1 for the case of cancelling the two strongest interferers. We let all the users to have an activity factor of $\beta = \{0.5, 0.75, 1\}$. It means that both the user of interest and the interferers are not active all the time. This is equivalent to having a re-use factor of 2 and $3/4$ in time and frequency. If we look at Figure 7, the throughput when we use these values for the re-use factor is less than the corresponding throughput with activity factor of one. This result tells us that under this scenario it is better to use the whole bandwidth all the time. It is important to highlight the fact that in this scenario, there is receiver that can cancel the strong interferers. If we have such a receiver, then it is optimal to use all resources or have a re-use factor of one. Having a re-use factor of one also means that the spectral efficiency is higher.

V. Conclusions

We propose to use a decentralized hybrid-ARQ retransmission protocol that employs incremental redundancy combined with a receiver that can cancel two strong interferers and we show that our scheme is effective at combating interference without requiring any coordination.

In the future work, we are considering to extend the model to consider MIMO systems and rate adaptation to optimize our hybrid-ARQ policy.

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