Relay-Aided Failover in Wireless Networks using Adaptive Power and Rate Unicast Scheduling

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***Abstract*—We present an adaptive power and rate TDMA scheduling algorithm for unicasting messages from base stations to their associated mobile clients in a cellular wireless network. To enhance network robustness, we consider a relay-aided system under which relay stations are placed in fixed locations in each cell area. Upon a base station failure, a relay station is capable of receiving unicast transmissions issued by a neighboring base station, or by a relay station placed in a neighboring cell. Our adaptive power and rate scheduling algorithm reacts to base station failures by reconfiguring the unicast schedule and packet distribution routes. The objective of this paper is to study the performance behavior attained for such a scheme under pre-failure and post-failure scenarios. We show that our failover scheduling algorithm is effective in adapting to base station failures, limiting the performance degradation incurred.**

I. Introduction

Cell outage management is a functionality that aims to automatically detect and mitigate outages that occur in cellular networks due to unexpected failures, and is an integral part of the Self-Organizing Network [1]–[3] concept for LTE systems [4], [5]. It is essential that the system has the capability to compensate for the outage-induced coverage and performance degradations during network failure events, such as the failure of base stations.

Various failover schemes have been previously studied. In [6]–[8], the authors adjust the pilot power, antenna tilt and azimuth to mitigate outage-induced performance degradations. The study in [9] automatically reconfigures the neighboring base stations of the failed cell by adjusting their transmit power levels for outage compensation. However, these papers neither consider changing the scheduling of the base stations, nor transmission rate adaptation in their compensation operations.

The use of relay stations in wireless communications systems is known to be effective to combat path loss and enhancing link quality for the underlying networks [10]–[12]. In these systems, fixed relays are deployed as part of the infrastructure to relay messages between base stations and mobile clients in a dual-hop fashion. For relay-assisted unicasting, [13] and [14] investigate scheduling algorithms with power adaptation (but not rate adaptation). [15] examines scheduling algorithms with dynamic time/frequency allocation in relay-aided cells without power or rate adaptation. [16] investigates scheduling algorithms with orthogonal bandwidth allocation with rate adaptation (but not power adaptation).

In this paper, we aim to develop scheduling algorithms with both power and rate adaptation to unicast messages to as many mobile clients as possible under the failover scenario. The algorithms enable base stations to coordinate, on a time-division basis, the transmission of downlink unicast packets to identified mobile clients. We also study the effectiveness of using relay stations to support the unicast transmissions in wireless networks under pre-failure and post-failure scenarios.

Upon the failure of a base station, our failover scheme assigns base stations that are neighbors of the failed cell to expand their coverage area by adjusting their transmit power and rate levels. If such an operation is not feasible, the failover scheme automatically configures mobile clients in the failed cell to receive unicast transmissions from nearby relay stations. The neighboring base stations then attempt to transmit the relevant unicast packets directly to such relay stations.

The system model is presented in Section II. In Section III, we present our unicast scheduling algorithms under pre-failure and post-failure operations. In Section IV, we evaluate the performance of the system under different joint scheduling schemes. Conclusions are drawn in Section V.

II. System Model

We consider cellular wireless networks whereby base stations are interconnected through a backbone network, and each cell is managed by a macro base station, such as LTE networks. Neighboring base stations (and relay stations, when employed) are time slot synchronized, and share their downlink channels on a coordinated spatial-TDMA basis. The time slot duration is assumed to be equal to the transmission time of a prescribed load of packets under the lowest acceptable signal-to-interference-and-noise ratio (SINR) level. Regional neighboring base stations interact and coordinate with each other to produce an effective TDMA schedule, and their transmit power and data rate levels are selected through the use of adaptive modulation/coding operation.

Each base station periodically transmits control signals and each active mobile client associates with the base station from which it receives the signal at the highest power. Base stations communicate through the shared use of control and data sub-channels. Mobile clients continuously monitor the quality of their reception channels, and use uplink control sub-channel to provide their channel quality information (CQI) to their base stations. The latter use this data to derive the propagation gains

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Fig. 1: Network layout of the relay-aided system

for their unicasting downlink channels. We assume here that such updates are executed at a sufficiently fast pace to be of relevance for the time period over which the underlying scheduling operation is performed. Note that CQI collection mechanism is part of the LTE infrastructure, and is included in the control plane [17].

In this paper, we assume that the base stations have tri-sectored antenna, and the relay stations use omni-directional antennas. Each base station is capable of adjusting its transmit power level continuously in $[0, P_{max}]$, while each relay station has an adjustable transmit power range of $[0, P_{Rmax}]$. The relay stations are positioned in fixed locations, at 0.7×distance from base stations to the edge of cell. Relay stations are symmetrically placed around the base station in each sector, as shown in Fig. 1. Under a given SINR level, base stations and relay stations can select to transmit packets at Shannon's rate. A mobile client can only receive a unicast packet successfully from either a base station or a relay station.

The channel propagation gain is modeled as $G_{ij} = \frac{1}{K d_{ij}^{\alpha}}$, where d_{ij} is the distance between the transmitter i and receiver j, α represents the path loss exponent, and K is a factor that accounts for absorption and penetration losses. We assume that the propagation gain matrix to be fixed during the period for which the schedule is calculated. Let $i_k \to j_k(r_k)$ and $P_{i_k}^{(t)} \in [0, P_{max}]$ denote a successful unicast transmission from base station i_k to mobile client j_k under rate r_k, at transmit power level P_{i_k} in time slot t. The unicast transmission scenario $S(t) = \{i_1 \to j_1(r_1), \cdots, i_M \to j_M(r_M))\}$ is defined as a candidate set of unicast transmissions that are considered to all take place in the same time slot t, where the receiving mobile clients are distinct. The unicast transmission scenario $S(t)$, under power vector $\bar{P}(t) = (P_{i_1}^{(t)}, ..., P_{i_M}^{(t)}),\ 0 \le P_{i_k}^{(t)} \le P_{\max},\ k = 1, 2, ..., M,$ is feasible if the SINR levels at all the receiving mobile clients are met:

$$\frac{P_{i_k} G_{i_k j}}{\sum_{l \neq k} P_{i_l} G_{i_l j} + N} \ge \gamma(r_k), k \in [1, ..., M] \quad (1)$$

where the threshold level $\gamma(r_k)$ depends on targeted bit error rates and the employed modulation/coding scheme (MCS).

The total number of packets required to be unicasted to all the mobile clients is determined by upper layer operations. Since the derivation of an optimal solution to this problem is NP-hard [18], we develop a class of computationally efficient heuristic algorithms for such coordinated relay-aided adaptive power and rate unicast scheduling.

III. Adaptive Power and Rate Unicast Scheduling Algorithms

In this section, we introduce our heuristic adaptive power and rate unicast scheduling algorithms and failover schemes. The first (basic) algorithm is a static coloring based scheduling algorithm, whereas the second algorithm is our main adaptive power and rate scheduling algorithm. The reason that we introduce the first algorithm is that it is simple and readily implementable, and is used as a baseline comparison to our adaptive algorithm.

A. Static Coloring Based Scheduling Algorithm

1) Coloring Algorithm with No Relays: We assume a TDMA oriented operation, such that under a k-color scheduling scheme, a time frame consists of k time slots. Under this scenario, a static 3-color scheduling scheme is considered, accounting for the tri-sectored antennas of the base stations. Base stations transmit at their max power level, and all simultaneous transmissions will have the same directionality. Base station downlink transmission rates are adapted by adjusting the employed code rate of the MCS to the SINR monitored at receiving mobile clients.

2) Coloring Algorithm with Relays: Under this scenario, a two-phase relay-aided coloring algorithm is utilized. During the first phase, base stations transmit to the relay stations and the selected set of mobile clients that are close to it, using a 3-color scheduling scheme (as described in Section $A1$). The selection of these mobile clients is performed by comparing the rate of transmitting directly to mobile clients from the base stations to that effective transmission rate through a relay station, whereby the latter is calculated as: 1/(effective tx. rate) = 1/(relay max tx. rate) + 1/(base station-to-relay station tx. rate). Generally, all mobile clients located in the center of a cell will receive packets directly from the base stations. Mobile clients located at the edge of a cell will only receive unicast packets directly from the base stations if the direct transmission rate is higher than the effective transmission rate.

Under the second phase, relay stations transmit to mobile clients using omni-directional antennas. Scheduling is again based on a 3-color scheme (instead of just a 1-color scheme) to avoid interferences between relay station transmissions. Thus, the resulting two-phase algorithm operates like a 6-color scheme. Generally, the use of a higher value of k value leads to degradation in throughput capacity levels. One way to improve the performance of this algorithm is to make use of beam-forming during the batch packet forwarding phase from the base stations to the relay stations. However, beam-forming is not considered in this paper.

B. Adaptive Power and Rate Scheduling Algorithm

1) Adaptive Algorithm with No Relays: Under the adaptive algorithm, each sector of the cell has a corresponding weight that expresses its current estimate of the highest throughput that can be realized unicasting packets to its associated mobile clients. Following the exchange of these weights within a two-hop base station neighborhood, each base station then compares its own weights with the advertised weights of its neighbors. Note that each weight has a directionality that associates with it, which is given priority. Base stations that advertised the highest weight in its neighborhood are declared as winners, and they are scheduled to unicast in this (first) time slot.

Based on the interference and noise levels reported by its mobile clients, each winning base station calculates the current SINR level incurred at the receiving mobile clients. Since each scheduled mobile client is guaranteed to receive its base station's signal at a SINR level that is higher than the required SINR threshold, the difference between the latter two identifies the current power margin level associated with signal reception at each mobile client. This power margin value identifies the amount of additional interfering power that a covered mobile client is able to sustain, without violating its receive SINR level requirement. Each winning base station proceeds to advertise to its neighbors the list of such interference power margins. The announced interference power margin levels impose constraints on the transmit power level that can be employed by base stations that are to be considered in the next iteration.

Unscheduled base stations consequently calculate their highest feasible transmit power level, and announces to its neighbors its new weight. The next winning base station (if any), is subsequently selected and scheduled to transmit at this time slot at its calculated maximum power level. The iteration continues this way until the interference power margin levels advertised for covered clients are not sufficient to permit an operation that accommodates the scheduling of an additional base station in this time slot. If there are still mobile clients to be covered, the algorithm continues to schedule transmissions in the subsequent time slot. A flow diagram of the adaptive algorithm is shown in Fig. 2.

The failover scheme under the no relay scenario operates as follows. When a base station failure is detected, the above mentioned algorithm will automatically attempt to adjust the transmit power and rate levels of base stations that are neighbors of the failed cell while synthesizing a new unicast transmission schedule for all base stations. Mobile clients that are located in the failed cell area are consequently associated with their new base stations.

2) Adaptive Algorithm with Relays: When using a relay-aided system, the adaptive algorithm starts by iteratively selecting a set of base stations with highest weight in their neighborhood to transmit in the first time slot (using the approach described in $B1$). Relay stations that have successfully received a unicast packet in a prior time slot serve as candidate

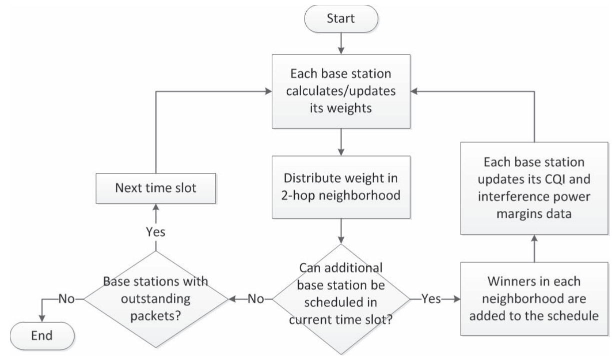


Fig. 2: Adaptive algorithm flow diagram

relay stations which may be scheduled and tasked to transmit their received unicast packets in subsequent time slots. Thus, the algorithm operation in the subsequent time slot is modified in that the list of nodes to be scheduled now includes not only unscheduled base stations, but also candidate relay stations (same applies to Fig. 2).

Base stations give priority to the packets to be forwarded to the relay stations, and only after that the base stations unicast packets to mobile clients with the best achievable rate levels. Each base station then advertises its weights, as well as the weights of its candidate relay stations to its neighbors. A winner in each neighborhood (which could be either base station or candidate relay station) is then determined and scheduled to transmit in the current time slot.

The failover scheme under relay-aided system operates as follows. Prior to the occurrence of a failure event, each relay station in each cell is associated with a backup base station (typically, the one closest to its location) and a relay station located in a neighboring cell. In case of a base station failure, each backup base station adds the post-failure relay stations that are associated with itself as members of its set of relay stations. It also includes relay stations in the failed cell that are affiliated with a relay station in its own cell as (potential) clients of the latter. Upon the occurrence of a base station failure, a mobile client that is located in the failed cell will select the strongest control beacon signals that it receives, and proceed then to form an affiliation with the station that issues this signal. Since each relay station is associated with a specific base station (and upon failure of its base station with the backup base station and an affiliated relay station), a post-failure association is formed between each mobile client in the failed cell and a specific neighboring base station or relay station. Subsequently, an impacted base station updates the list of mobile clients that it is associated with, as well as the set of relay stations with which it is affiliated with.

With the inclusion of this control mechanism, the algorithm automatically adjust the transmit power and rate levels of base stations that are neighbors of the failed cell while synthesizing a new unicast transmission schedule for all base stations. As needed, it will also employ and schedule direct and indirect relay stations to reach as many mobile clients as possible that are located in the area of the failed cell.

IV. Simulation Results

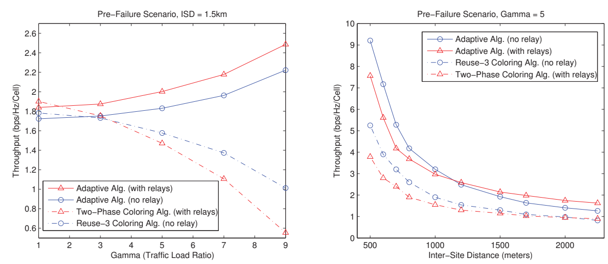
We used MATLAB to simulate and analyzed the performance of our algorithms in a cellular wireless system. We set P_{max} = 40W and P_{Rmax} = 10W. The prescribed bandwidth is 5 MHz. Base stations and relay stations are capable of adjusting their MCS. The noise power density level N_0 is set to be -174 dBm/Hz. The path loss exponent is selected to be 3.68, and the path loss constant level is 40 dB [19].

The radius of each cell is denoted as R. The inter site distance (ISD) is denoted as D. Assume cells to be modeled as hexagonal forms, we have $D = \sqrt{3}R$. The base station that manages the i^{th} cell is denoted as base station i. We selected an area of geographical coverage and fixed the number of mobile clients to be 1400 (which are uniformly distributed in the cell areas). The number of cells employed depends on the underlying ISD considered. For example, when ISD = 1km, there are 35 cells in the network.

In Fig. 3(a), under the pre-failure scenario, we compare the throughput as a function of Gamma, where the latter represents the level of heterogeneity in traffic loading for each cell. For example, Gamma = 9 implies that the highest-loading cell in the system has nine times more traffic than the lowest-loading cell. When Gamma = 1 (uniform traffic loading across all the cells), we observe that our adaptive algorithm achieves a slightly lower throughput performance than that attained under the static coloring algorithm. This is because the coloring algorithm produces the best schedule under this condition. However, our adaptive algorithm increases in performance as Gamma increases, whereas the static coloring algorithm degrades under the same condition. The adaptive algorithm is capable of adapting its schedule to the heterogeneous traffic loading levels by allowing more time slots to be allocated to cell sectors with higher outstanding packets for transmission. Conversely, this adaptive scheduling element does not exist for the coloring algorithm. We further observe that with the employment of relay stations in the network, the performance of the adaptive algorithm increases for all values of Gamma. However, this is not the case for the coloring algorithm, since allocated time slots are wasted (for base stations which have low traffic loading level) as Gamma increases.

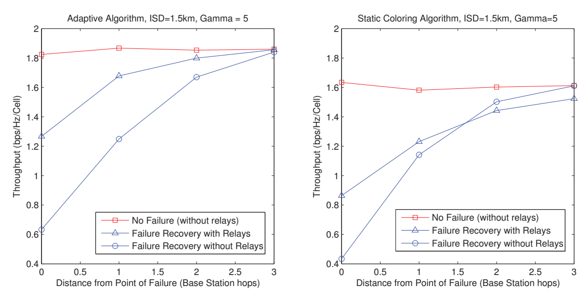
To access the effect of ISD on the performance of our algorithms under the pre-failure scenario, we set Gamma equals to 5, while varying the ISD from 500 m to 2250m. We observe from Fig. 3(b) that when the ISD level is below 1200m, the adaptive scheduling algorithm that employs no relay station exhibits the best performance behavior, since the system operates mainly in interference limiting mode. We also observe that the coloring algorithm achieves a worse throughput, due to the heterogeneous traffic load. For longer ISD levels, the system tends to operate in noise limiting mode. As ISD increases, the addition of relay stations increases the performance for both the adaptive and coloring algorithms.

Under the post-failure scenario, we assume that there is a base station failure in the center location of the network. In Fig. 4, we compare the throughput as a function of the distance from the point of failure (in base station hops). Under the simulated scenario (ISD = 1.5km, Gamma = 5), when a base station fails, we observe that the adaptive algorithm achieves a throughput degradation of 30% at the failed cell (Distance = 0) under the relay-aided scenario. This represents twice the performance improvement from that achieved under the no relay case. On the other hand, the static coloring algorithm achieves better throughput performance with the employment of the relay stations at the failed cell. However, it fails to take advantage of the relay-aided system with its two-phase scheduling approach, as observed from the throughput performance moving away from the point of failure. As a result, even though the coloring scheduling algorithm is simple to implement, and is very efficient under homogeneous traffic load, the adaptive algorithm is required to achieve efficient operation under heterogenous traffic load.



(a) (b)

Fig. 3: Pre-failure throughput vs. (a) Gamma (b) ISD



(a) (b)

Fig. 4: Post-failure throughput vs. distance from point of failure for (a) adaptive algorithm (b) coloring algorithm

V. Conclusions

In this paper, we study failover schemes (with and without relay stations) for unicasting in wireless cellular networks. Our adaptive power and rate scheduling algorithm is based on the iterative scheduling of base stations that realize the highest throughput in their two-hop neighborhood. Following the failure of a base station, our failover schemes lead to the dynamic selections of transmit power and rate levels, in scheduling unicast transmissions by neighboring base stations and relay stations to provide best coverage to mobile clients in the failed cell area while assuring a high ensuing throughput rate performance.

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