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Robust cross layer optimization in relay aided cellular networks

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Abstract A robust optimization framework for cross layer optimization is proposed to deal with time varying channels, reducing the required channel state feedback overhead and giving strong QoS guarantees. Lower bounds for the achieved *goodput* when robust scheduling is used are derived and through simulation we study the impact in terms of blocked calls and QoS achieved by the robust solution for two different cell topology layouts: when 2-hop relaying is allowed and when only direct base station to user transmissions are allowed. The results reveal that the price of robustness is lower for the 2-hop case than the single hop case.

Keywords Robust optimization · Relay networks · Scheduling · Price of robustness · Cellular networks

List of symbols and variables

Sets

N Set of all nodes (base stations, relays and users), with elements $n = 1, \ldots, |N|$;

L Set of all links (transmitter and receiver node pairs), with elements $l = 1, \ldots, |L|$;

R Set of available modulation and coding schemes, with elements $r = 1, \ldots, |R|$;

U Set all users, with elements $u = 1, \ldots, |U|$;

Λ Set of transmission groups, with elements $i = 1, \ldots, |\Lambda|$;

$L(n)$ Set of links adjacent to node n;

$\mathcal{P}$ Set of paths between a base station and a user, with elements $p = 1, \ldots, |\mathcal{P}|$;

$\mathcal{P}(l)$ Set of paths traversing link l.

Optimization variables

p_l Transmit Power allocated to link l;

r_{pu} Rate through path p for user u;

θ_{lr} Binary variable indicating if link l is active and transmitting using modulation and coding scheme r;

λ_i Airtime/resources proportion devoted to transmission group i;

c_{li} Instantaneous rate for link l in transmission group i;

s_u Slack between allocated data rate and the user u demand;

π_l Dual value associated with the capacity constraint for link l;

π_l^j Dual value associated with the capacity constraint for link l after iteration j in the column generation algorithm;

q Dual value associated with the airtime constraint;

q^j Dual value associated with the airtime constraint after iteration j in the column generation algorithm;

ω_u^j Dual value associated with the demand constraint of user u after iteration j in the column generation algorithm.

Parameters

W Noise power level at the receiver;

G_{kl} Instantaneous power attenuation (random variable) between the transmitter of link k and the receiver of link l;

$\bar{G}_{kl}$ Average power attenuation between the transmitter of link k and the receiver of link l;

c_r Data rate when using modulation and coding scheme r;

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γ_r Signal to noise plus interference ratio threshold for modulation and coding scheme r;

d_u Data rate demand for user u;

δ_{kl} Random variable with mean describing the instantaneous power attenuation between the transmitter of link k and the receiver of link l;

t_c Channel coherence time, i.e. the time between two channel states;

t_s Schedule validity period, i.e. the time between system state changes;

t Elapsed time between two consecutive resource allocations.

1 Introduction

Future cellular networks will require the support of increasingly high data rates to mobile users. Inevitably, as the data rate requirements increase, cell coverage must decrease and more cells need to be deployed, driving up operator's operational and capital expenditures. Fixed regenerative relays that are able to expand the natural coverage of their home base station have been proposed has a cost effective technology to improve coverage and capacity [4, 12, 14]. Notwithstanding the advantages of multi hop networks, the complexity of managing the network is considerably increased. Dynamic management of radio resources and intelligent relay selection rules, in the case of 2 hop relay networks, are needed to combat potentially higher interference levels and highly variable loads.

There has been a strong interest on radio resource management techniques focusing in QoS guaranteed multi hop networks [1, 11, 13, 16]. These proposed techniques require accurate channel state information (CSI) and most are centralized. Given that the channel state is time varying, allocations constructed with nominal estimates of channel states need to be reconstructed every time the channel conditions change or the performance of the whole system might be compromised. Channel feedback information may produce significant overhead over the scarce resources of the wireless interface and hence consume significant portion of the actual capacity. In addition to that, if wireless resources are controlled by radio network controllers they may also stretch the utilization levels of the wireless access network. Addressing this issue we propose schedules that remain feasible for a large set of channel realisations, allowing for less frequent schedule updates and ensuring QoS. This would permit scheduling and relay selection to operate on the seconds range, following long term channel variations, instead of the milliseconds range as current cellular standards propose.

To deal with random channel states we propose a robust optimization framework for cross layer optimization. Although robust optimization procedures have been proposed to deal with small scale fading in the context of power control [10, 18, 19] surprisingly little work has been reported in the cross layer radio resource management literature dealing with uncertainties in the propagation conditions. In [17] a robust scheduling framework is proposed for spatial time division multiple access networks to deal with uncertainties in the power attenuation factor in the presence of lognormal shadowing and showed that there is an optimal robustness level minimizing the cumulative average time slots. The present work builds on the former by considering a larger class of channel statistics and assessing the impact on the achievable end to end throughput in multi hop networks—the trade offs are explored through numerical simulations in both single and multi hop cellular networks.

In this paper the joint admission control, routing and scheduling optimization problem is formulated as a Linear Program that can be solved by a column generation procedure corresponding to finding feasible sets of concurrently active links. By considering the robust counterpart of the scheduling sub-problem a closed-form probabilistic bound on the end to end throughput is derived. Through numerical simulations the trade-off between robustness and capacity is evaluated in both traditional single hop cells and the proposed two hop cells. It is found that in two hop relay cells there is a less stark trade-off between reliability and capacity when compared to the traditional cellular paradigm.

The rest of the paper is organized as follows. The system model is described in Sect. 2. In Sect. 3 we formulate a Linear Program guaranteed to maximize the number of admitted users and in Sect. 4 present an optimization algorithm based on column generation guaranteed to find the optimal operating point. In Sects. 5 and 6 we show how to guarantee that the constructed schedule does not loose any transmissions, bounding the probability of a failed transmission and the achievable effective throughput (or goodput). Section 8 shows simulation results comparing the different relaying schemes. Finally, Sect. 9 concludes the paper.

2 System model

Consider a cellular system where cell edge coverage is complemented by the use of two hop relaying by in-band non-transparent, regenerative relays (RS). This scenario corresponds to relay concepts proposed by 3GPP's LTE-Advanced standard. No frequency planning is in place, i.e. all transmitter nodes share the same frequency to transmit. We assume that all transmitting nodes share the same bandwidth with multiple access done in a STDMA fashion, i.e. airtime is divided between groups of spatially separated concurrent transmissions. Time is assumed to be continuously divisible. Each user has a data rate demand to be satisfied during a frame. The maximum rate at which a transmitter and node pair, link $l \in L$ (where L is the set of all links), can communicate in any time slot depends on the achievable signal to interference plus noise ratio (SINR) denoted by γ. We further assume that the transmitter can only choose from a finite set of transmission modes (modulation and coding schemes), R, each with a corresponding rate c_r and a minimum SINR threshold γ_r for which the modulation and coding scheme achieves its maximum throughput value. If the SINR falls below this threshold the transmission is assumed not to be successful and an outage occurs, i.e. the throughout falls to zero for that time period. Although this assumption might be too conservative, it is justified by the sharp decrease in throughput of practical transmission modes as the SINR drops [6].

For a given transmit power p_l the SINR of link l is calculated as:

$$\frac{G_{ll}p_l}{W + \sum_{k \neq l} G_{kl}p_k} \tag{1}$$

where in the above expression W represents the noise power level at the receiver and G_{kl} the effective power attenuation from the transmitter of link k to the receiver of link l. The power attenuation depends on path loss and other effects that depend on the propagation conditions at the time of transmission. The average power attenuation is given by the path loss, $\mathbf{E}[G_{kl}] = \bar{G}_{kl} = 10^{-\frac{PL_{kl}}{10}}$ with $PL_{kl} = f_c + \eta \log_{10}(D_{kl})$ where f_c is the minimum path loss that depends on the carrier frequency, η is the path loss exponent and D_{kl} the distance between the transmitter and receiver.

A rayleigh flat fading model is considered where the instantaneous power attenuation follows an exponential distribution and is given by $G_{kl} = \bar{G}_{kl}\zeta$ where ζ is an exponential distributed random variable with intensity 1. It is further assumed that for each time slot the instantaneous link gain is independently distributed.

2.1 Scheduling

Time is divided into frames composed by multiple time slots. In each time slot a subset of links is active (in the media access sense) such that: no two links sharing a node are active (avoiding packet collisions) and each active link transmits with a data rate such that a corresponding SINR target is satisfied. We assume that the average power attenuation and the channel model are known to a centralized scheduler, but no information about the channel realization is available. We further assume that the path loss remains constant for the time duration of the scheduled period and that if a link's SINR level falls below its threshold an outage occurs and the information is lost.

We denote by Λ the set of all feasible subsets of active links, called transmission groups in the terminology of [9]. Each element of Λ is denoted by i. Let c_{li} be the instantaneous rate at which link l transmits in group i and λ_i the proportion of airtime given to group i, i.e. the fraction of available transmission slots where the set of links in group i are active. The data rate of link l is then given by $\sum_{i \in \Lambda} \lambda_i c_{li}$. Note that the fraction of time each group is active must not exceed one: $\sum_{i \in \Lambda} \lambda_i \leq 1$.

2.2 Relay selection

Users can be served by the base station directly or through two hop paths corresponding to each available relay station in the cell to which the user has been assigned or a combination of both schemes (multi path routing). Typically few paths are considered as some relays would clearly be inefficient to serve the user. All paths for which the user is closer to the corresponding relay than the base station, as well as the direct single hop path are considered. Let r_{pu} be the data rate over path p for user u. If user u has data rate requirements d_u then, in order to satisfy the user's demand, we require that the sum of the data rate in each path be greater or equal than the data rate demand, i.e. $\sum_p r_{pu} \geq d_u$.

We consider three distinct cases: all users are served directly by the base station (Single Hop Routing); all users are served by the closest relay (Single Path Routing); users can have their flow split between multiple paths and these are chosen in tandem with scheduling and admission control (Multi Path Routing).

In any case, all links need to support the data rate assigned to paths traversing it: $\sum_{p \in \mathcal{P}(l), u \in \mathcal{U}} r_{pu} \leq \sum_{i \in \Lambda} \lambda_i c_{il}$, where $\mathcal{P}(l)$ is the set of paths traversing link l. For example, the BS–RS1 link has to support all the data rates of all users being served by RS1. The feasibility of a path depends on the schedule as defined by the link rate vector in each transmission group and the airtime each group is given.

2.3 Admission control

If a user's demand can not be satisfied the user is not admitted into the system. Let r_{pu} be the allocated rate over path p for user u as determined by the routing and scheduling protocols. Let $s_u = d_u - \sum_p r_{pu}$ be the difference between the user's allocated rated and its demand, clearly if s_u is positive the user's demand is not satisfied.

Consequently user u is admitted if and only if s_u is non-positive. Given a set of users U, then we are interested in admitting the greatest number of users possible.

To admit the greatest number of users into the system we need to construct a feasible schedule and allocate users to a suitably selected RS or BS. In the next section we propose a Linear Programming solution to minimize the number of users not allocated.

3 Linear programming formulation

The integrated admission control, scheduling and routing problem (ACSR) can be formulated as a Linear Program (LP) minimizing the slack between a user's demand and the allocated rate. Note that each time a user arrives or departs the system the problem does not need to be solved from scratch as the LP solver can be *warm started* with the previous allocation. The LP is given by:

$$\begin{aligned} &\text{Minimize: } \sum_{u\in U} s_u \\ &\text{Subject to, } s_u + \sum_{p\in P} r_{pu} = d_u \forall u \in U \\ &\sum_{p\in \mathcal{P}, u\in U} a_{lp} r_{pu} \leq \sum_{i\in\Lambda} c_{li}\lambda_i \forall l \in L, \\ &\sum_{i\in\Lambda} \lambda_i \leq 1, \lambda \geq 0, s \geq 0, r \geq 0 \end{aligned} \tag{2}$$

The first set of constraints ensures that the users demand is satisfied if and only if $s_u = 0$; the second constraint (capacity constraint), where a_{lp} is a parameter taking the value 1 if path p traverses link l or not, ensures that the flow through all links can be scheduled; the third constraint (time sharing constraint) guarantees that all transmission group's fractions of airtime does not exceed the total; finally the last set of constraints guarantees that all variables are positive—guaranteeing that no user gets more than the corresponding data rate demand.

Let s^* be an optimal basic feasible solution to the LP. If all users can be scheduled then $\sum_u s_u^* = 0$, otherwise there will be some $s_u^* > 0$; furthermore, no user u' with $s_{u'}^* > 0$ could have attain their demand without at least one other user u with $s_u^* = 0$ having to drop out of the system. This property results from the fact that in an optimal solution to any LP at most m variables are non zero (where m is the number of constraints) and the convexity constraint, $\sum_{i\in\Lambda} \lambda_i \leq 1$. It follows then that the maximum number of users that can be admitted in the system such that all achieve their required data rate is given by the number of users with $s_u = 0$, whenever all users have the same data rate demands. An admission control protocol could then admit all users with $s_u = 0$ and reject all users with $s_u > 0$. If users have different data rates it could be the case that dropping one heavy data rate user would allow many small data rate users to be admitted. However it is not clear that admitting many low data rate users is preferable to admitting a few high data rate users or vice versa. The above formulation allows both solutions to be *optimal*, as in our view the preference is application dependent. Nonetheless, by properly weighing the objective function users can be given preference—for example, if the objective function is $\sum_{u\in U} \frac{1}{d_u} s_u$, users with lower data rates would be preferable than users with high data rates.

Linear programming admits a polynomial algorithm in the number of variables and constraints. However there is an exponential number of possible transmission groups in the number of links; therefore solving (2) with off the shelf Linear Programming algorithms is impractical for a large number of users. Moreover enumerating all feasible transmission groups is a challenge in itself. To deal with this issue we propose a column generation algorithm in the next section.

4 Column generation algorithm

Column Generation is a general method to solve large mathematical programmes with many variables and few constraints. In each iteration a subset of the variables are considered and 'new' variables are added as needed. Björklund et al. [3] used column generation to minimize the frame length in STDMA scheduling and Johansson and Xiao [9] proposed it as a unified framework to maximize network utility.

Let Λ^j be a restricted subset of transmission groups under consideration at iteration j. In each iteration j the LP in 2 is solved to optimality with only the transmission groups in Λ^j. Let π^j be the associated dual values of the capacity constraint and q^j the associated dual value of the time sharing constraint of the restricted LP in iteration j. A transmission group i that maximizes the *reduced cost*, $\sum_l \pi^j c_{il} - q^j$, is generated; that is, in each iteration, a transmission group that allows for the greatest reduction in the objective function value, is generated. The generated transmission group is added to the set of considered transmission groups, $\Lambda^{j+1} = \Lambda^j \cup i$. The procedure is repeated until the maximum reduced cost is non positive—i.e. until no further transmission group can improve on the current optimal solution.

Note that in every iteration a lower and upper bound on the optimal solution to the full problem is obtained. The lower bound is given by: $\sum_u \omega_u^j d_u - \sum \pi_l^j c_{il}$, where ω_u^j is the dual value associated with the demand constraint of each user u (this property follows from proposition 1 in [7]); the upper bound is given by the optimal $\sum_{u\in U} s_u^j$.

In Fig. 1 the above procedure is illustrated in a flow chart. There is no guarantee that the optimal solution is found before all columns are generated; nonetheless, we remark that this does not occur in practice and optimality is usually reached with a small subset of columns.

4.1 Optimal transmission groups

Transmission groups that maximize the reduced cost in iteration j can be generated through the solution to a mixed integer linear program (MILP). For ease of notation the superscript j is dropped from all variables as we now focus on operations occurring on each iteration of the column generation algorithm. Let θ_{lr} be a binary variable taking the value 1 if link l is active and transmitting with the modulation and coding scheme r belonging to the set of available coding schemes R and offering data rate c_r with a corresponding SINR γ_r. Given that a link can only transmit

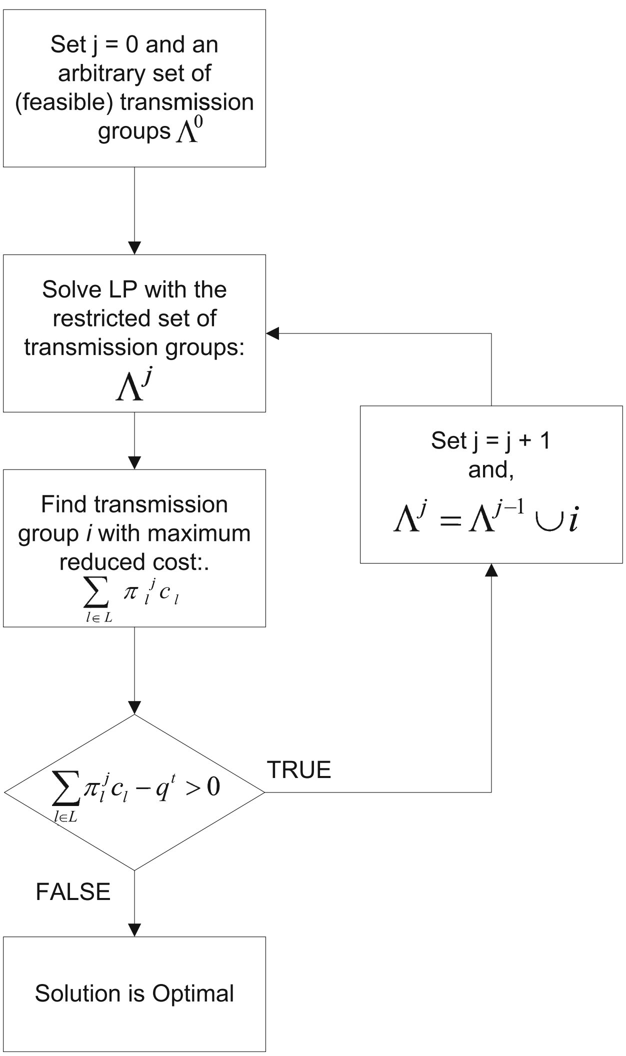


Fig. 1 Flow chart for the column generation algorithm

using one modulation scheme at a time, the data rate achieved by a link in a transmission group, c_{li}, is given by $\sum_r c_r \theta_{lr}$. The transmission group is then composed by all links l with $\theta_{lr} = 1$ for some $r \in R$. The maximum reduced cost transmission group is given by the optimal solution to:

$$\text{Maximize:} \sum_{lr} \pi_l c_r \theta_{lr}$$

$$\text{Subject to,} \; p_l \le P_{max} \sum_r \theta_{lr} \qquad \forall l \in L \tag{3}$$

$$p_l \ge \frac{W\gamma_r}{\bar{G}_{ll}} \theta_{lr} \qquad \forall l \in L, r \in R \tag{4}$$

$$\frac{\bar{G}_{ll} p_l + (1-\theta_{lr})M}{W + \sum_{k \ne l} \bar{G}_{kl} p_k} \ge \gamma_r \qquad \forall l \in L, r \in R \tag{5}$$

$$\sum_{r, l \in L(n)} \theta_{lr} \le 1 \qquad \forall n \in N \tag{6}$$

$$\theta_{lr} \in \{0,1\}, p_l \ge 0 \tag{7}$$

Constraints (3) and (4) are binding constraints for the variables θ_{lr} and p_l. Constraint (5) ensures that all active links in any time slot satisfy the signal to noise ratio (SINR) threshold for the given modulation scheme r if and only if $\theta_{lr} = 1$ (link l is active and using scheme r)—the constant M is set to be big enough such that whenever $\theta_{lr} = 0$ (link l is not active using scheme r) the constraint is satisfied regardless of its power allocation. Constraint (6), where $L(n)$ is the set of links that have node n as a start or end point and N is the set of all nodes, requires that only one link per node is active.

Note that in formulating this problem, the average link gain is used as the effective link gain, reflecting the lack of information about the channel realization at the time of scheduling.

4.2 Sub-optimal transmission groups

General mixed integer programming is in NP-hard and, as such, efficient algorithms to solve MILP's are not known. However it can be trivially shown that if we generate a (sub-optimal) transmission group with $\sum_{lr} \pi_l c_r \theta'_{lr} \ge \epsilon \sum_{lr} \pi_l c_r \theta^*_{lr}$, with $\epsilon \le 1$, such that $\sum_{lr} \pi_l c_r \theta'_{lr} < q$ at iteration j^*, then the optimal solution to the original full problem, $\sum_u s^*_u$, is at most a $O(\epsilon)$ factor from the optimal solution of the restricted problem $\sum_u s^{j^*}_u$; that is, if we can guarantee that the reduced cost of the generated transmission groups are at most ϵ away from the optimal transmission group, then the full routing, scheduling and admission control algorithm will also be ϵ away from the optimum.

Off the shelf MILP solvers can usually generate efficient solutions with a low optimality gap; furthermore, efficient heuristics to solve this transmission group problem have been proposed in the literature such as [5] and [15]. Therefore a column generation algorithm with sub-optimal transmission groups could be used in practice to solve the ACSR problem, while giving strong guarantees on the system performance. However, given that the feasibility of a transmission group depends on the channel conditions at the time of transmission and these are time varying, constructed schedules could suffer from adverse instantaneous channel conditions. To overcome this problem we propose in the sequel a Robust Scheduling approach ensuring that transmission groups remain feasible for a large set of possible channel realisations.

5 Effective throughput under uncertain channel states

The instantaneous SINR of a scheduled link might drop below its threshold due to channel state variations. Let p_{il} be the probability of a link failure transmitting in group i in any given time slot. This depends on the channel state at that instant and the allocated power for each link in the transmission group. Given that some transmissions will not be correctly received we are interested in obtaining a lower bound on the end-to-end proportion of a flow over a path that is correctly received by each admitted user. For notational convenience let k denote a path/user pair (u, p). Then r_k^* is the data rate flow for path/user k as determined by the optimal solution to the ACSR problem. The amount of correctly received stream of packets or goodput for all users is given by $\sum_k x_k r_k^*$, where x_k is the proportion of correctly received flow for path/user k. The proportion of correctly received flow for the entire system (effective throughput ratio) is given by:

$$\frac{\sum_k x_k r_k^*}{\sum_k r_k^*} \geq x \quad \text{for some, } \{x \in [0,1] : x > x_k \forall k\} \tag{8}$$

Let λ_i^* and c_{il}^* denote the optimal proportion of time of group i is active satisfying condition (11) and the capacity of link l in group i respectively as determined by the optimal solution to the ACSR problem. Assuming independent channel variations for all links and two consecutive slot the effective data rate of link l is given by $\sum_i \lambda_i^* c_{il}^* p_{il}$.

Theorem 1 *The proportion of correctly received flow for all paths/users pairs, x_k, is bounded from below by $(1-\beta)^{n_k}$ for some $\beta < 1$ and $p_{il} < 1 - \beta$ where n_k is the number of hops of the path/user k.*

Proof First note that the proportion of a link capacity devoted to a path/user k' is given by $\frac{r_{k'}^*}{\sum_{k \in P_l} r_k^*}$, where P_l is the set of paths over link l. Thus, for a link in path/user k, $l \in L(k)$, the data rate is given by $\frac{r_k^*}{\sum_{k \in P_l} r_k^*} \sum_i \lambda_i^* c_{il}^*$ and the effective data rate by $\frac{r_k^*}{\sum_{k \in P_l} r_k^*} \sum_i \lambda_i^* c_{il}^* p_{il}$. The ratio of these two quantities gives the proportion of correctly received flow at the end point of link l. x_k can then be found by multiplying these ratios along the path.

$$x_k = \prod_{l \in L(k)} \frac{\sum_i \lambda_i^* c_{il}^* p_{il}}{\sum_i \lambda_i c_{il}^*} \geq p^{n_k} \\ \text{for some } \{p \in [0,1] : p > p_{il} \forall i, l\} \tag{9}$$

where n_k is the number of hops along the path. From the definition of β we have $p \geq 1 - \beta$. □

For a fixed maximum number of hops, $\bar{n}$, the goodput ratio can be bounded:

$$\frac{\sum_k x_k r_k^*}{\sum_k r_k^*} \geq (1-\beta)^{\bar{n}} \tag{10}$$

It should be noted that the above discussion relates to a system where no retransmissions of data packets occur. If retransmissions are allowed in each hop, errors can be assumed to not propagate for a sufficiently high number of retransmissions. Therefore, the end to end data rate in any path is constrained by the worst link on the path, i.e. x_k is bounded by $1-\beta$ for any number of hops. Hence, with a retransmission protocol the effective throughput is not affected by the number of hops. Naturally, the delay effectively increases linearly with the number of hops.

In the next section we propose a Robust Optimization framework where links are scheduled in such a way that β can be made arbitrarily close to zero.

6 Robust generation of transmission groups

Optimization problems are sensitive to uncertainties in their parameters. To overcome this problem, the robust optimization paradigm has been proposed. Robust optimization deals with data that can take any value in a given bounded set, typically described by an ellipsoid and relying on solving a second order cone program. This approach is unsuitable to deal with problems where some of the variables are restricted to take only integer values, as in mixed integer programming. Overcoming this limitation the authors in [2] proposed an approach where the resulting robust counterpart is a linear program. In this approach the coefficients are substituted by pessimistic values that are controlled by a robustness level.

Since variations in the channel conditions can adversely affect a transmission over a link a given schedule might not remain feasible; estimating the actual link gain and recomputing the optimal schedule every time the channel changes is difficult if not impractical. However nominal values for the link gain, based on the average link gain and channel statistics, can be used. This is mainly under the assumption that the probability of failure can be bounded by a small constant, there is no need to recompute the schedule every time the propagation conditions change.

Recall that G_{lk} is the effective link gain, i.e. the power attenuation for the instantaneous channel realization, between the transmitter of link l and receiver of link k. In Sect. 4.1 the SINR constraint is only guaranteed for the average link gain values. That is a link's SINR does not drop below its threshold with probability 1 if its own gain G_{ll} is greater than its average $\bar{G}_{ll}$ and the gains between the receiver of l and the transmitter of other active links G_{kl} are lower than their respective averages $\bar{G}_{kl}$. Otherwise the probability of a link failure is non zero. To minimize the probability of a link failure we substitute the average gains by pessimistic values that guarantee that the SINR constraint is not violated for a larger set of channel realisations. Let $G^- \leq 1$ be a pessimistic factor for a link's own channel gain, and $G^+ \geq 1$ a pessimistic factor for the interferers gains. Transmission groups are then generated such that each link's SINR satisfies:

$$\frac{G^- \bar{G}_{ll} p_l}{W + \sum_{k \neq l} G^+ \bar{G}_{kl} p_k} \geq \gamma_r \qquad (11)$$

Note that the parameters G^- and G^+ can be set in a per link basis—when the channel statistics for each link are different lower robustness values maybe set for links with lower variance. In order to simplify our exposition we concentrate on the case, without loss of generality, where the PDF shape of the power attenuation is the same for all links.

As previously stated, the instantaneous power attenuation, G_{lk} can be described by $\bar{G}_{lk}\delta_{lk}$, where δ_{lk} is a random variable with expected value 1. Assuming that the power allocation is done such that inequality (11) is tight, i.e. the constraint is satisfied at equality, we are interested in choosing G^- and G^+ such that the probability of 11 being violated is minimized, i.e.

$$Pr\left\{\frac{\delta_{ll}\bar{G}_{ll}p_l}{W + \sum_{k \neq l} \delta_{kl}\bar{G}_{kl}p_k} < \frac{G^- \bar{G}_{ll} p_l}{W + \sum_{k \neq l} G^+ \bar{G}_{kl} p_k}\right\} \qquad (12)$$

In [17] the above equation is bounded assuming that δ_{kl} follows a log normal distribution. Herein we show a bound for exponentially distributed fading link gains.

Theorem 2 *Let i be a transmission group such that the transmit power allocation for all active links l using transmission scheme r satisfies ineq. (11) and δ is an exponential distributed random variable with mean 1. Then, the probability of a link failure in transmission group i is bounded from above by $1 - e^{-G^-}$ or, if the interference is non-zero, by $1 - e^{-2\frac{G^-}{G^+}}$.*

Proof Let $n - 1$ be number of active interferers in group i and let $u_0 = \bar{G}_{ll}P_l$, $u_1 = W$ and $u_i = \bar{G}_{il}P_i$ for interferer $i = 2, \ldots, n$. Ineq. (12) can then be written as:

$$Pr\left\{\frac{\delta_1 u_0}{u_1 + \sum_{i=2}^{n} \delta_i u_i} < \frac{G^- u_0}{u_1 + \sum_{i=2}^{n} G^+ u_i}\right\} \qquad (13)$$

Manipulating both sides we get,

$$Pr\left\{\frac{\delta_1}{G^-} < \frac{\delta_2 u_2 + \cdots + \delta_n u_n + u_1}{G^+(u_2 + \cdots + u_n) + u_1}\right\}$$

$$= 1 - e^{-\frac{G^- u_1}{G^+(u_2+\ldots+u_n)+u_1}} \frac{1}{\prod_{i=2}^{n} 1 + \frac{G^- u_i}{G^+(u_2+\cdots+u_n)+u_1}} \qquad (14)$$

$$\leq 1 - e^{-\frac{G^- u_1}{G^+(u_2+\cdots+u_n)+u_1}} \frac{1}{\exp\left(\sum_{i=2}^{n} \frac{G^- u_i}{G^+(u_2+\ldots+u_n)+u_1}\right)} \qquad (15)$$

$$\leq 1 - e^{-\sum_{i=1}^{n} \frac{G^- u_i}{G^+(u_2+\cdots+u_n)+u_1}} \qquad (16)$$

$$\leq 1 - e^{-G^-}$$

Equation (14) follows directly from the analytical expression for $Pr\{z_1 \leq \sum_{i=2}^{n} z_i + c\}$ where all z_i are exponential distributed and c is a constant [10]. Ineq. (15) comes from $\prod_i 1 + x_i \leq \exp(\sum_i x_i)$ for all $x_i \geq 0$. If $u_2 + \ldots + u_n > 0$ then ineq. (16) is bounded by $1 - e^{-2\frac{G^-}{G^+}}$. □

6.1 The impact on spatial reuse and coverage

The bound in 2 and inequality (10) show that the proportion of effective throughput can be made arbitrarily close to 1 for appropriate values of G^- and G^+. Naturally as the robustness levels increase, the opportunity to spatially reuse the channel and achievable data rates are reduced. A trade-off between QoS (effective throughput and delay) and the number of users that can be served is apparent. In what follows we assume that $G^- = 10^{-\alpha\lambda}$ and $G^+ = 10^{\alpha\mu}$.

This trade-off can be made explicit by considering how the cell area offering a given modulation is affected by increasing G^-. For simplicity and without loss of generality, consider a circular cell where the path loss is given by $d^{-\eta}$, where d is the distance between the transmitter and receiver, and a maximum RF power level of P. The maximum distance between two nodes, d_{max}, that supports a modulation scheme with a corresponding SINR threshold γ is given by:

$$d_{max} = 10^{-\frac{\alpha\lambda}{\eta}} \left(\frac{P}{W\gamma}\right)^{\frac{1}{\eta}} \qquad (17)$$

The coverage area falls at a slower rate as α increases than the bounds given by theorem 2. Note that the coverage

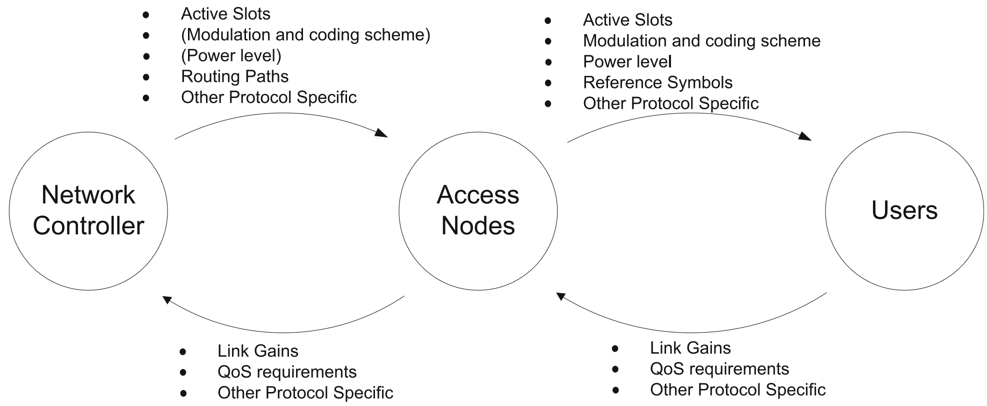


Fig. 2 Information flow during a scheduling period

area can be maintained constant by increasing the transmission power.

Similarly we can evaluate how the minimum reuse distance of a modulation scheme d_{min}, i.e. the minimum distance between a receiving and an interferer node for a fixed transmitter distance (d) and RF power, changes with the robustness parameters (assuming negligible noise power):

$$d_{min} = 10^{\frac{\alpha(\lambda+\mu)}{\eta}} \gamma^{\frac{1}{\eta}} d \tag{18}$$

As above, the bound given for the Rayleigh channel model when noise is negligible falls quicker while increasing α than the minimum reuse distance increases.

These results show that there is scope to increase the robustness of the system without significantly sacrificing its performance—particularly if the system is under utilized. At low levels of system utilization spare resources can be utilized and the spectral efficiency of each transmission may be decreased, thus enabling an increase in the parameter α at no extra cost. However for high utilization levels, where all users must be served at the highest possible spectral efficiency, there is little incentive to increase the robustness level since some users may inevitably have to be dropped. In this case there is a sharp trade-off between admitted users and QoS.

7 Overhead reduction

In this section we provide an analysis on the overhead reduction when using a robust scheduling framework. The fact that schedules are robust to channel state variations have two implications on the protocol overhead. First the effective link gain need not to be collected every instance the channel changes, reducing the communication overhead; second, schedules and routes can be updated less often, reducing the computational overhead. We note that for fast fading channels recomputing a schedule every time the channel conditions change is impractical and, as we demonstrate in the next section, not accounting for possible changes has a detrimental effect in the QoS experienced by users; this implies that, regardless of any communication and computational overhead that may be saved by robust scheduling, the performance of the system (in the sense of guaranteed QoS) is improved by accounting for possible adverse fading.

7.1 Communication overhead

If schedules and routes are constructed in a centralized controller, the controller needs to inform the access nodes and users of: the serving paths, the assigned transmission slots, and the power levels and/or modulation and coding schemes to use[1]. The users must inform the access nodes about their channel quality and application dependent QoS requirements; this information is then passed on to the scheduler. Figure 2 illustrates the information flow between the intervenient nodes.

Depending on the particular protocol/standard used the amount of bits necessary to encode the necessary information used may vary. Nonetheless, for T transmitters and R receivers of which $|U|$ are users (note that the RS are both receivers and transmitters), $O(TR)$ bits need to be reported due to the link gain information, $O(|U|)$ bits to be reported related to the QoS requirements for a total of $O(TR + |U|)$ bits of overhead in the uplink; in the downlink $O(R + T)$ bits need to be sent. If scheduling occurs every time the channel changes (non-robust case) and the coherence time of the channel is given by t_c the total overhead is in $O\left(\frac{TR+|U|+T+R}{t_c}\right)$. With robust resource allocation the schedule needs not to be updated while it remains a valid schedule; it only needs to be updated to track long term trends in the average link gain and user's arrivals and departures. Let t_s be the average schedule

[1] When using link adaptation or power control this may be decided at the access node; in which case stronger QoS guarantees may be given, but maintaining an high overhead between transmitter and receiver.

validity time. The communications overhead is reduced by a factor of $\frac{t_c}{t_s}$.

Different standards have different protocol overheads, we analyze the 3GPP's long term evolution (LTE) standard as described in [8] for possible overhead reductions. Channel estimation is done by having the base stations transmitting reference symbols along with other symbols every 1 ms slot to track the instantaneous channel response. This accounts for about 6 % of the total available bandwidth. As only the long term average response needs tracking in our framework the frequency for which reference symbols should be transmitted can be reduced: if instead of transmitting every time slot these are transmitted every 10 ms frame we could get 100 samples in 1 second, sufficient to track slow to moderate speed users while reducing the reference symbols overhead by a factor of 10. After estimating the channel response the user reports back the results. This is set to occur on a periodic basis or at the request of the transmitter. When periodic reporting is set, reporting occurs between 2 and 160 ms using 11 bits. Control information (used resources id, modulation and coding schemes) is transmitted in every time slot occupying 1–3 symbols, implying an overhead of 7–14 %.

7.2 Computational overhead

Similarly to the analysis above we consider the reduction on the computational complexity of a general scheduling algorithm. The authors in [20] defined the time amortized complexity of a wireless scheduling algorithm as $\chi = \lim_{T\to\infty} \frac{1}{T}\sum_{t=0}^{T} \chi(t)$, where $\chi(t)$ is defined as the instantaneous scheduling complexity at time t. If scheduling occurs less often the amortized complexity is reduced by the same factor; that is, the complexity can be reduced by a factor of $\frac{t_c}{t_s}$.

7.3 Schedule validity period

When users are stationary the schedule remains valid while no users depart or arrive because the long term path loss remains constant. In this case the validity time of the schedule is given by the average user driven inter-event times: the average time between a user arrival or departure. Note that, when a user arrives or departs the system the LP in 3 need not to be solved from scratch. For arriving users, the columns identified in the previous scheduling period can remain and only columns relative to the new arrival need to be generated. Similarly, for a departing user, the columns dealing with this user may be dropped, while maintaining the other columns.

For mobile users the schedule needs to be updated more frequently—or the robustness level increased. Let d_t be the distance between the user and the transmitter at time t. As the user moves away from the transmitter the drop in SINR is given by $\left(\frac{d_t}{d_0}\right)^{\eta}$. It can easily be seen that the probability of a link failure at time t, assuming Rayleigh fading, is upper bounded by:

$$P(\text{link fails at time}\, t) = 1 - e^{-G^{-}\left(\frac{d_t}{d_0}\right)^{\eta}} \tag{19}$$

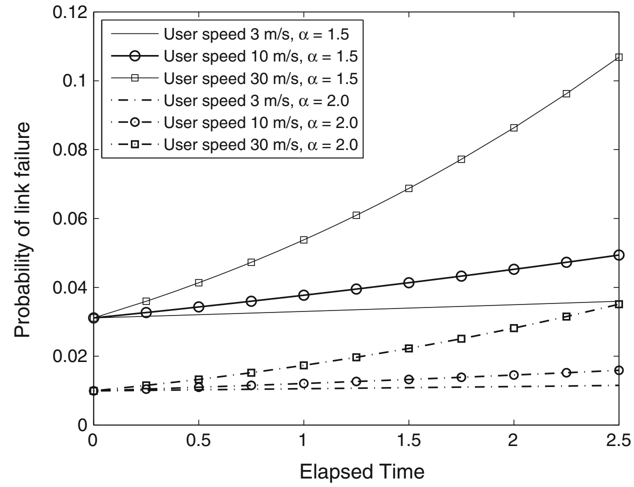


Fig. 3 Upper bounds on the probability of a link failure at different times since the schedule construction for different user speeds and robustness levels where $G^{-} = 10^{-\alpha}$; higher robustness level allows for a lower scheduling frequency

For a given relative user speed it is possible to estimate for how long the schedule remains feasible with high probability, and hence decide on the scheduling frequency. Note that this frequency can be traded-off with a higher robustness level: for lower G^{-} the probability of a link failure remains low for a greater relative displacement ratio, $\frac{d_t}{d_0}$. Figure 3 illustrates this for different values of G^{-} and user's relative velocity. As it can be seen the scheduling frequency can be greater than 1 second even at high speeds for a moderate robustness level without a big penalty on the link failure probability. For walking speeds of 3 m/s, the probability of a link failure grows less than 0.1 % after 5 seconds. Notice that, for rayleigh fading, the channel coherence time for a user speed of 3 m/s is below 10 ms—reducing the overhead by a factor of 500.

8 Numerical investigations

A three cells cluster with relays as in Fig. 4 is considered. Two relays are placed at half the radius of the cell at equal distance from each other, dividing the cell in three parts. Users are uniformly distributed each with the same data rate demand (1 Mbps). For the relay aided case users are

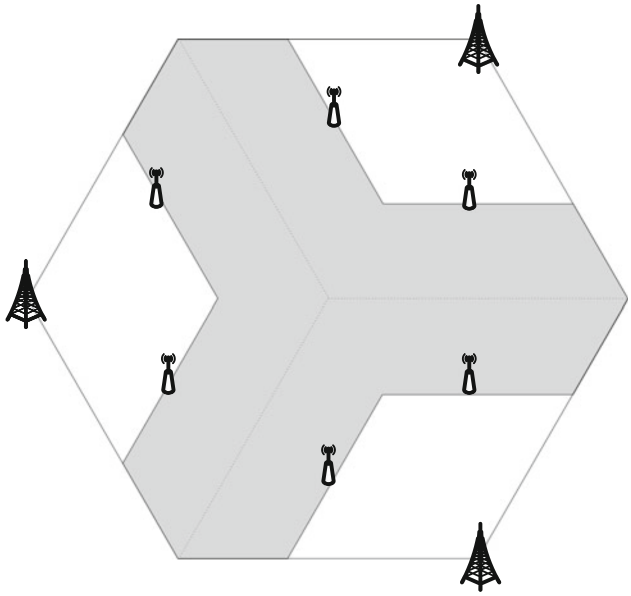


Fig. 4 Three cell cluster topology with coverage enhancing relays. Users located in the shaded area are served by their closest relay in the single path scheme

Table 1 Simulation parameters

Parameter	Values
Cell radius	1 km
Carrier frequency	2 GHz
Bandwidth	10 MHz
Maximum RF power	20 W
Rates @10 MHz	12, 25, 43 Mbps
SINR thresholds	5.56, 11.26, 20.25 dB

associated with the closest relay and in the single hop case all users are served directly by the base station. Assuming that relays are equipped with better antennas and are at a higher level above ground than users, the path loss between relays and base station in dB is given by, $PL_{BS\text{–}RS} = 125.2 + 36.3\log_{10}(d)$; for the RS–UE and BS–UE the path loss is given by $PL_{BS/RS\ -\ UE} = 131.1 + 42.8\log_{10}(d)$. Where d is the distance between the nodes expressed in km.

The robustness parameters are given by $G^- = 10^{-\alpha}$ and $G^+ = 10^{\alpha}$, thus 10α is the protection in dB accounting for each link's fading to account for variations in the interferers effective link gain. The rest of the simulation parameters can be found in table 1.

Monte Carlo simulations are performed in 200 cases, each with 30 users deployed. For each case we solve to optimality the robust scheduling problem for different levels of α ranging from 0 to 2.4. Note that when $\alpha = 0$, only the long term path loss is being considered. The

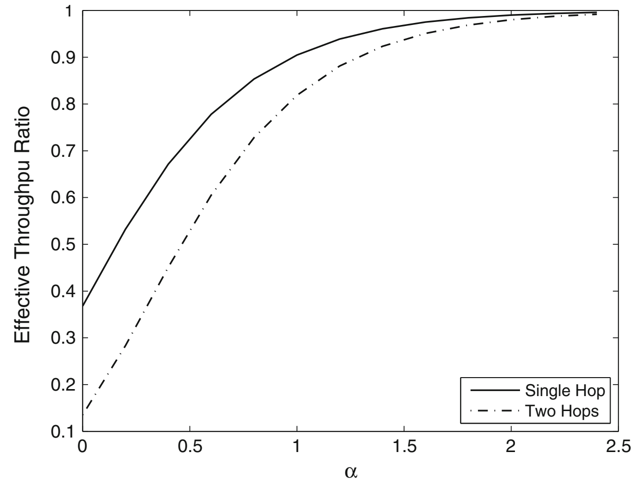


Fig. 5 Bounds on the effective throughput ratio as a function of α for the single hop case and the 2-hop relaying case

effective throughput and probability of a link failure are estimated by averaging over all cases. Two corner case scenarios are considered: a uniform user distribution, where user's positions are drawn from an uniform probability distribution over the entire cell space and a edge users scenario, where users are placed inside the shaded area in Fig. 4.

8.1 End to end rate guarantees

The single-hop scheme can provide better guarantees in terms of the effective throughput ratio than the 2-hop relaying scheme. Nonetheless, the impact of using an extra hop can be compensated for with higher levels of robustness. In Fig. 5, the theoretical bounds on the effective throughput ratio are plotted for different levels of α. The figure shows that when we can guarantee that >90 % of injected data reaches the destination without corruption, the difference between the guarantees for single hop case and 2-hop case is negligible; that is, for sufficiently high levels of robustness the impact of the extra hop is negligible. As the ideal operating point, purely in terms of QoS, would be an effective throughput ratio above 90 % the extra hop adds little impact.

In Fig. 6 the theoretical bound is compared with results from our simulation for the 2-hop case. Note that for $\alpha > 1.8$ the bound is tight and we can guarantee more than 90 % of injected data reaching its destination.

8.2 The price of robustness

As highlighted in Sect. 6.1 as the probability of a transmission failure approaches zero, so does the achievable link rate which, in turn, could reduce the throughput rate that the

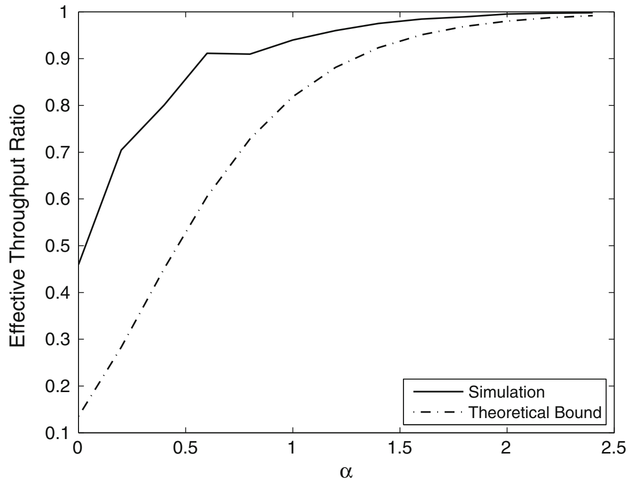
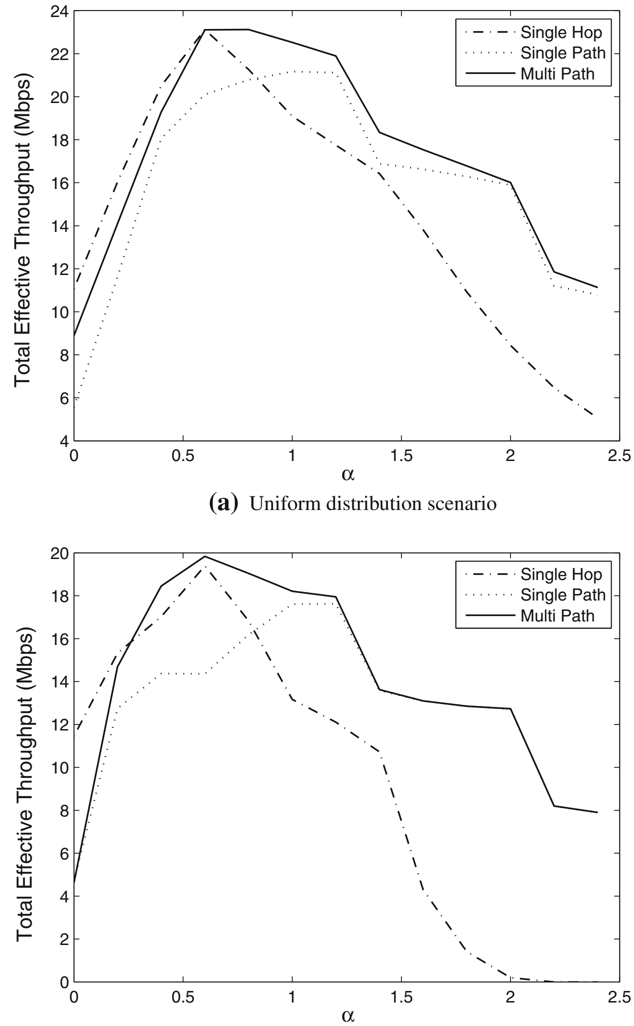


Fig. 6 Theoretical bound versus simulation results on effective throughput ratio

system can support. This implies that the total effective throughput may not always increase as the probability of a link failure approaches zero. Figure 7 illustrates this point. In the uniform case, for $\alpha \leq 0.6$ the total effective throughput grows for all routing schemes, reaching its maximum at 23.1 Mbps; at that point the achievable total effective throughput is reduced for the Multi Path and Single Hop routing schemes. A similar behaviour is seen when only edge users are considered, with the throughput peaking at 19.8 Mbps. The Single Path routing scheme achieves its maximum at $\alpha = 1.2$ offering a total effective throughput of 21.1 Mbps in the uniform case and 17.6 Mbps in the edge users case. Note that, by jointly optimizing routing and scheduling (multi path scheme) we are able to offer higher throughput; for $0.2 < \alpha \leq 0.6$ the multi path scheme mainly chooses the direct paths and for $\alpha \geq 1.2$ follows the single path routes. When only edge users are considered, the multi path scheme offers higher throughput than both the single path and the single hop schemes for $0.2 \leq \alpha \leq 1.2$; when users are uniformly distributed the multi path scheme offers higher throughput for $\alpha \geq 1.2$. This is due to the ability of using a combination of both schemes. In the second scenario, for $\alpha = 0$ the multi path scheme is offering the same total effective throughput as the single path scheme. This is because for all schemes at $\alpha = 0$ the optimal solution of the master LP (2) is $\sum_{u \in \mathcal{U}} s_u^* = 0$, and as no information on the robustness of a path is present in the master problem the routes are chosen to be the ones given by the optimal solution for the single path. To ensure that the paths chosen are always the more robust we could solve a robust counterpart of the original LP, however we note that when robust scheduling is in use, $\alpha > 0$ this effect is not present and as such we believe that the increased complexity of solving a Robust LP is not warranted.

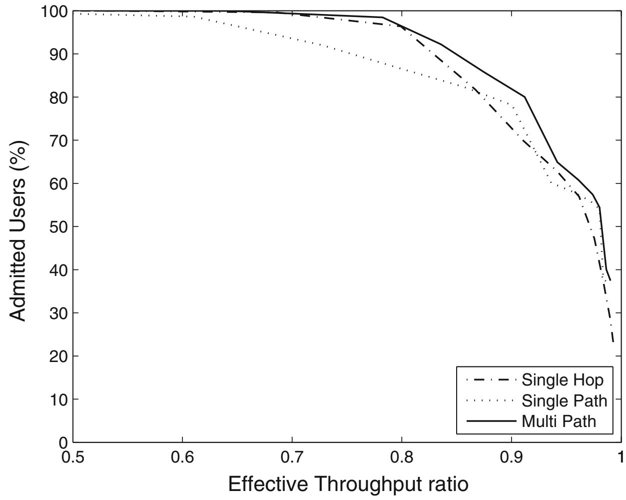


(a) Uniform distribution scenario

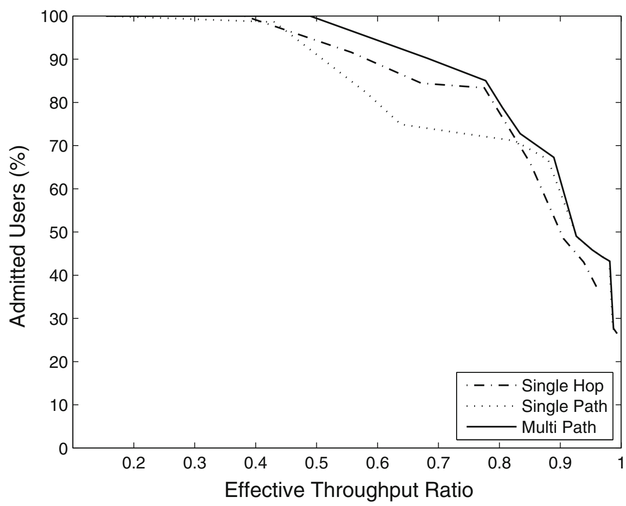
(b) Cell edge scenario

Fig. 7 Total effective throughput as α increases

The total effective throughput ratio is maximized using the multi path scheme for $\alpha = 0.6$. Even though this is when the system's throughput is maximized the QoS experienced by users in the system might be too low, due to a high volume of dropped data or delay incurred in packet retransmissions. For $\alpha = 0.6$ the effective throughput ratio is 0.77—implying up to 23 % of packets being retransmitted or lost. This could be unacceptable in terms of QoS. To increase the experienced QoS, we have to sacrifice the system's throughput and consequently the number of admitted users. Figure 8 shows the QoS experienced by the users, in terms of effective throughput ratio, and the percentage of users admitted into the system. For an effective throughput ratio smaller than 0.6 we can accommodate almost all users (90 %) with the single hop paths in both scenarios. However, to offer an effective throughput ratio greater than 0.90 the single hop system can only serve 69 % (48 % of the users in the second scenario). In



(a) Uniform distribution scenario



(b) Cell edge scenario

Fig. 8 Trade-off curves between quality of service and number of served users

contrast, the two hop system can accommodate up to 80 % of users (67 % in the cell edge scenario) while offering an effective throughput ratio of 0.90. In this sense, two hop relaying has a lower price of robustness as we can serve more users at a higher level of QoS. It is worth noting that for high levels of robustness jointly optimizing the schedule and relay selection does not seem to give meaningful performance improvements. Simple relaying schemes in this case are sufficient, which reduces the system's complexity considerably.

9 Final remarks and conclusions

In this paper we formulated the joint admission control, scheduling and relay selection problem in a relay-aided cellular network as a Linear Program. To overcome a high computational complexity in solving the full linear program a low complexity procedure based on column generation was proposed, where low complexity scheduling techniques previously proposed can be used. This cross layer procedure requires centralized knowledge of the propagation conditions and accordingly we propose a robust scheduling framework to immunize the constructed schedules to adverse channel state variations.

In real scenarios the channel might follow different distributions, namely the product of small and large scale effects; nonetheless we stress that the proposed methodology can be used to deal with more realistic scenarios, even if no closed formula bound on the probability of a link failure can be established. In this case numerical methods can be used in guiding the choice of the appropriate values for G^{-} and G^{+}. A key assumption in deriving these results was the independence of the gain factor between links and slots; it is an open research question on how to tune the robustness parameters when time-correlated and space-correlated power attenuation factors exist.

The numerical results have highlighted the trade-off between the number of admitted users and QoS. With a higher level of robustness we can guarantee a better QoS for users but the number of concurrently active users must decrease. The price of robustness revealed by the numerical simulations might be too high to appeal to system designers: to achieve a 0.95 effective throughput ratio 40 % of the users had to be blocked. However with time correlated channel states we could achieve a lower price of robustness by collecting channel states periodically—albeit not as frequently as to create too much overhead—and get better point estimates of the true channel state rather that just the average state, this would allow the scheduler to be less conservative (use a lower α) and therefore accommodate a higher number of users. Moreover, adaptive modulation and/or power control can also be used to combat fading and prevent outages at the expense of a higher protocol overhead; however the overhead in using adaptive modulation or power control should be lower than centralized scheduling, as no feedback to a central controller is needed to perform adaptive modulation or power control, therefore schedules that are able to operate on a longer time scale can still reduce the channel state feedback overhead while giving strong guarantees on QoS. If different classes of traffic are present, for example delay tolerant and non tolerant, we could offer different levels of robustness for the different traffic classes; delay tolerant users could admit less robust transmissions, as the packet delay induced by re-transmission could be tolerated, while for inelastic applications the short term data rate is critical in assuring QoS.

In conclusion, we detail a framework for the design of robust cross layer systems suitable to deal with natural variations in the instantaneous channel conditions. This allows the system to guarantee QoS to users. The numerical results presented herein are encouraging as they show that the robustness of the system can be parameterized by using a single parameters; this allows to control the necessary trade off between QoS and capacity.

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