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Modeling and Analysis of Dynamic Pilot Scheduling scheme for 5G Ultra-Dense Network

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Abstract—Recently, Ultra-Dense Network (UDN) has been evolved as one of the key enablers of future 5G wireless technologies. Thus with UDN, more users will be served simultaneously by densely deployed small cells in a confined geographical area. Such dense deployment however amplifies the problem of interference, frequent handover and frequent rescheduling of users in mobility case due to reuse of same radio resource after smaller distance. This paper describes the analysis of a dynamic pilot resource allocation scheme of UDN system where mobile users transmit periodically uplink (UL) pilot signals. Such periodic UL pilot transmission scheme enables user localization and channel estimation. The analysis considered the number of pilot resources needed to serve a given user density and how often the system has to reallocate pilot resources when interference conditions are changing for mobile users. The result on average time between consecutive reallocation of pilot resource of a mobile user gives a good insight on how timely the UDN system has to serve mobile users.

Index Terms—UDN, UL pilot, (re)scheduling, reuse distance.

I. INTRODUCTION

It is expected that 5G system design will support higher capacity per km² and more connections when compared to the current generation of wireless network. Network densification is identified as one of the key network level solutions to serve such increased service demand [1], [2]. In ultra dense network (UDN), cell size can be only tens of meters. UDN has potential in boosting area capacity, enhancing the end-user experience and providing short range transmission with high line of site (LoS) probability. However, a major drawback of increasing the cell density is that the overall interference in the network also increases due to reuse of same channel after smaller distance in mobility scenario [5]. In small cells, the amount of handover also increases significantly. Therefore, there is a need to handle handover as efficiently and infrequently as possible [7].

One proposal which is aimed to tackle the dense cell problems such as inter cell interference (ICI), frequent hand over (HO), and mobility management is user centric UDN approach [6] and [12]. In this approach, an intelligent network having controller at edge is responsible for dynamically assigning group of small base stations called transmit receive points (TRPs) to a serve each user equipment (UE) seamlessly. It also performs scheduling decisions, handover and mobility management based on continuous measurement of user location information. This solution requires tracking user location with

the help of user specific uplink (UL) beacons [8]. In UL based beaconing approach, users periodically transmit UL beacons (also called pilots) in time division duplex (TDD) system and the network uses those for tracking user location and estimating channel state information (CSI). In TDD system, these uplink pilots will also provide downlink CSI, because TDD reciprocity implies that the uplink and downlink channels are mathematically identical. In order to do that, users should be assigned either orthogonal pilot resources or the same pilot resource after guaranteed reuse distance so that the interference will be minimal. Interference aware pilot resource allocation for CSI estimation has been investigated before in [3]. However, the work in [3] does not answer the question how many orthogonal pilot resources are needed for given users density.

Increased usage of time-frequency resources for pilot transmission increases the number of available orthogonal pilots, but this is obtained at the cost of data resources. In network design, one is interested to keep the right balance between pilot and data resource by finding the optimum amount of pilot resources needed. In practical networks, there are only limited set of pilot sequences with good cross correlation properties. Therefore, this necessitates reuse of these sequences after certain distance.

To serve large number of users, a method has to be devised for pilot resource management. The problem is to decide the number of orthogonal pilot resources needed for a given user density and how to reallocate resources when users are moving. In user mobility environment of UDN, interference due to users sharing same pilot resource will change dynamically. In order to minimize the interference, the pilot resources have to be reallocated. Hence, it is imperative to devise a framework of dynamic pilot resource reallocation scheme by taking into account user mobility and wireless propagation characteristics. Since each rescheduling needs network signalling, the need for reallocation has to be minimized such that the signaling overhead in the network would be at the tolerable level. Furthermore, for mobile users, a network designer needs to know how long, in time, will the assigned channel be valid before rescheduling is needed and what is the probability that the reallocation will find suitable resource, i.e. it will be successful.

Inspired by the aforementioned limitations, this paper

presents the analysis of dynamic pilot scheduling scheme of UDN. We use stochastic geometry approach due to its mathematical tractability. The analytic results are validated via simulations.

The remainder of this paper is organized as follows. Section II illustrates the system model and analysis. We provide numerical results with discussion in Section III. Conclusion is given in Section IV.

II. SYSTEM MODEL AND ANALYSIS

We consider two scenarios. In the first case, users are static and distributed in deployment area according to the known two dimensional homogeneous Poisson point process (PPP) with density λ as shown in Fig. 1. TRPs are deployed 50 m apart from each other. We considered an UL case where scheduling of users to transmit pilot (i.e. used for CSI estimation) is based on circular protection zone (also called exclusion area) of radius R . The pilot resources are allocated such that within protection area around a user, no other user is assigned the same pilot resource. The protection zone mitigates any interference arising from the transmission of concurrent UEs within protection area. The pilot allocation process can be described by thinning the initial PPP process. In order to maximize the signal to interference plus noise ratio (SINR), the allocation also takes into account the minimum interference criteria among candidate users for same pilot resource allocation. System state is reviewed periodically in each transmission time intervals (TTIs) and the pilot resource allocation is updated for users whose movement has violated the exclusion area constraint. The channel model used is the generalized path loss function ($D^{-\alpha}$) which is the dependent on distance (D) and path loss exponent (α) for all links. In the second case, users are moving according to a discrete time random way-point mobility (RWPM) model with zero thinking time [9].

The focus here is on two system parameters: namely the number of orthogonal pilot resources needed for allocation and how often the reallocation has to be carried out in user mobility. These parameters are derived from static and dynamic system analysis as described in subsequent subsections.

A. Static System Analysis

From the PPP model of the user distribution, the probability of getting n number of users in protection area at initial allocation case is given as:

$$P(N(A) = n) = \frac{(\lambda |A|)^n}{n!} e^{-\lambda |A|} \quad (1)$$

where $A = \pi R^2$ is the protection area. The probability that we can have up to N users in that area is given as:

$$PrN = \sum_{n=1}^N P(N(A) = n) \quad (2)$$

Given A , N and correspondingly PrN , the target here is to find optimum number of channels (N_{ch}) such that protection area constraint is satisfied. Among N number of users in

Fig. 1. Deployment scenario describing exclusion area and location of UE's and TRP's.

protection zone, there can be multiple users who share the same pilot resource as far as they are distance R away from each other. Consequently, if we reserve N channels for scheduling, the probability of having more than N users in area A is $1 - PrN$. Also, the probability that we fail to schedule users using N pilot resources is upper bounded by $1 - PrN$. We can bound the allocation failure probability if we reserve N_{ch} channels such that:

$$N_{ch} \rightarrow \min_{n_i} \sum_{n_i=1}^{\infty} P(n(A) = n_i) \leq P_{outage} \quad (3)$$

where P_{outage} is the target allocation outage probability. Note that, the limit selected from Equation (3) is a conservative bound. It assumes that for given N users in A each user in area A has unique pilot.

Once determined the number of pilot resources needed for scheduling from Equation (3), the next task is to schedule users to access channel based on fulfillment of exclusion area criteria and minimum interference criteria as follows.

- In exclusion area criteria, a resource is assigned to a user such that the same resource is not reused within exclusion area.
- In minimum interference criteria, among resources which satisfied the exclusion area criteria (ch), the one with minimum interference is selected, i.e.

$$ch^* = \operatorname{argmax} SINR(ch) \quad (4)$$

The minimum interference criteria forces to have balanced number of users per channel.

The described allocation process is also known as thinning process. After scheduling users, the density of users sharing the same channel (λ_{ch}) can be upper bounded by:

$$\lambda_{ch} = \frac{1 - e^{-\lambda \pi R^2}}{\pi R^2} \quad (5)$$

Note that Equation 5 does not take into account the minimum interference criteria in Equation (4).

B. Dynamic System Analysis

When users move following RWPM model, the interference constraint set in static case becomes invalid as the exclusion area constraint is no more holding. One approach to mitigate the interference in mobility scenario is to dynamically reallocate channel to users that fail to satisfy the reuse distance constraint. For moving users, we are interested in the average time interval between consecutive reallocations. The reallocation frequency reflects the signaling overhead the allocation process generates. The longer the time interval, the lesser is signaling needed for arranging the reallocation.

Consider a user moving distance d as shown in Fig. 1. To determine the probability that a moving user will have high interference due to violation of protection zone constraint, the change in protection zone is modeled using a moving circle. So, dA in Fig. 1 is the portion of the area where mobile user will have a chance of having another users sharing the same channel. The probability of getting interference after moving d distance is:

$$P_d = \frac{dA}{A} \quad (6)$$

From the geometry of circle, the area of asymmetric lens in which the circles intersect can be obtained from [10] and then from it dA is given as:

$$dA(d) = A - \left(2 \cdot R^2 \cdot \arccos\left(\frac{d}{2R}\right) - \left(\frac{d}{2}\right) \sqrt{4 \cdot R^2 - d^2} \right) \quad (7)$$

Since the system information is periodically updated after some TTIs, it is discrete. It is sufficient to evaluate the interference situation only at discrete time moments, correspondingly at user moving steps, $k = 1, 2, \dots, K$.

The probability that the first occurrence of concurrent transmission within exclusion area requires moving k discrete steps without rescheduling is:

$$P(k) = P_d \cdot (1 - P_d)^{k-1} \quad (8)$$

The average time till reallocation (τ) is:

$$\tau = \frac{d \cdot \left(\sum_{k=1}^K (k \cdot P(k)) \right)}{v} \quad (9)$$

III. NUMERICAL RESULTS

In this section, we validate the analytic expressions derived to characterize dynamic scheduling scheme via simulation. In particular, the performance of UDN is illustrated using parameters such as: density of users using same resources,

Fig. 2. Density of users sharing the same pilot resource versus the exclusion distance.

the average time needed till rescheduling and probability of reallocation failure. The modeled deployment area has dimension $2 \times 2 \text{ km}^2$. In RWPM model, a user selects a random direction at start and keeps on moving towards the selected direction with constant speed, $v = 10 \text{ m/s}$. We evaluate the system as a discrete system such that in each step a user gets displaced d m away from its previous location and the corresponding statistics of parameters is collected. The simulation length during a drop is $S = 600$ steps. The transmit power is set to be at -30 dBm for UEs, path loss exponent α is 3, $d = 2 \text{ m}$, $\lambda = 800 \text{ UE/km}^2$. For reuse distance of $\{50, 100, 150, 200 \text{ and } 250 \text{ m}\}$, the corresponding number of users/resources are $N_{UE} = N_{ch} = \{9, 33, 70, 130 \text{ and } 140\}$ respectively with outage probability shown in Fig. 4.

Fig. 2 shows the simulation and analytic result of average density of users sharing same pilot resources. Density of users sharing same resources decreases with the increase of reuse distance R . From Equation 5 we can see that as R is increasing, $1/\pi R^2$ becomes dominant as compared to the numerator which seems to converge to 1 for larger R . Therefore, λ_{ch} is inversely related to R^2 . Besides, the Fig. 2 shows that simulation result is upper bounded by analytic result due to the fact that simulation has taken in to account minimum interference criteria given on Equation (4). Furthermore, the simulation result tries to captured the analytic value for larger R .

Fig. 3 shows the analytical and simulation plot of average time required before rescheduling a user moving with speed 10 m/s . These time values inherently show how swiftly the system/scheduler has to respond for a mobile user in a dense network. Also, the simulation result is lower bounded by analytic one. This is because of usage of the conservative bound in Equation 3 and use of minimum interference criteria in simulation. Hence the simulation result gives superior values

Fig. 3. Average time between reallocation versus reuse distance.

Fig. 4. Probability of rescheduling failure for different exclusion distance.

of time till reallocation compared to the analytic ones.

Fig. 4 shows the probability of rescheduling failure after users changed their location. The red line shows simulation result of probability of rescheduling failure and the blue line is its analytic counter part (outage probability bound obtained from Equation 2). Simulation results are upper bounded by the analytic values for reuse distance of less than or equal to 100 m. For reuse distance greater than 100 m, the simulation values tend to have zero outage while the analytic upper bound is not zero.

Fig. 5 shows probability of rescheduling users per step. Red line is the simulation result that shows percentage of rescheduled users per step of move. The one in blue shows the probability of getting interference after moving distance (d)

Fig. 5. Probability of reallocation per step, where in each step all users (moving at $v = 10$ m/s) get displaced $d = 2$ m away from their previous locations.

which is taken as upper bound for the chance of rescheduling. It is clear to see from the result that the probability of rescheduling users per step (i.e. percent of rescheduled users per step) is rather low, although all 3200 users are moving and displaced at each step. Hence, per step signaling overhead can be considered as very low. Moreover, in transition from one step to another, the serving TRP of a user could change (the change being agnostic to user) but the assigned pilot resources will be kept as far as reuse distance constraint is satisfied. This inherently reduces the unnecessary rescheduling (i.e. signaling overhead) in UDN.

IV. CONCLUSIONS

In this paper, we analyzed the performance of dynamic pilot scheduling scheme under UDN deployment scenario. Dense networks are expected to suffer from challenges like: interference as result of mobility, frequent handover, frequent rescheduling and rescheduling failures. This work describes the analysis on the number of needed orthogonal pilot resources and how often the network has to reallocate them for a given user density. Results show that the average reallocation times are in order of tens of seconds. That illustrates the stress dense network poses on the reallocation protocol in the controller at edge of UDN system. This average time interval between consecutive allocations gives a good insight how swiftly the UDN system has to perform reallocation of pilot resources for mobile users.

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