Effects of Load Dependent Dynamic Biasing and Association Order for Cell Range Expansion

Yifei Huang, Lachlan Bell, Salman Durrani, Xiangyun Zhou and Nan Yang
Research School of Engineering
The Australian National University, Canberra, Australia
Email: {firstname.lastname}@anu.edu.au

***Abstract*—Cell range expansion is a popular technique to encourage more user association towards small cells for heterogeneous networks to improve overall system performance. However, a constant bias value may be unsuitable for higher loads as it may lead to overloading. We propose a load dependent dynamic bias function which decreases the bias value with increasing load, acting as a natural prevention of overloading. Linking user association and biasing, we also investigate the effects of two different association orders and show that associating closest users first produces higher sum rate and average pico user rate than associating farthest users first, yet associates fewer users. Mathematical derivation of equivalent static biases that associate the same number of users is also presented to aid bias configuration. Our results indicate that dynamic biasing can bring improvements in rate performance, and is most beneficial when a minimum rate constraint is not imposed by the small cells.**

***Index Terms*—Heterogeneous networks, user association, cell range expansion.**

I. Introduction

Heterogeneous networks consisting of macro, pico and femto cells are expected to continue to be a key feature of future wireless networks. In current cellular networks, users are associated to the base station (BS) that provides the maximum received signal strength [1]. This may result in the macro being overloaded since its transmit power is orders of magnitude larger than small cells, and leaves small cells under-utilized. To aid a more even distribution of user association, biasing and cell range expansion (CRE) has been proposed [2] where a bias or weighting is given to a small cell such that users are more likely to associate to a small cell even if its potential data rate may be less than that it would receive from a macro.

Commonly, a constant or static bias value is picked (usually ranging between 3 dB to 15 dB) for a picocell to attract more users [3]. However, each user's service will be affected by the number of other users being served by the same cell on the same subchannel. Therefore, this load dependence means that a constant bias may quickly overload a pico, as the same capturing potential would exist regardless of how much load there already is. In light of this issue, we propose using a dynamic bias as a function of the pico cell load as a natural means to prevent overloading.

The concept of an adaptive/non-constant bias has been teased in the literature, e.g., [4], [5], and shown to be beneficial compared to constant bias value, but falls short of describing a bias function or incorporating load dependence. Optimal bias values are difficult to determine, and are empirically chosen via extensive simulations. In [6], bias values were incremented depending on the ratio of their uplink to downlink demands. An interesting approach was given in [7] that modeled BSs and users as electric charges each with a Gaussian potential function. Notably, it was found that the approach was marginally better than CRE using constant bias values of 3 dB and 6 dB. An optimization approach to user association with load considerations was studied in [8], [9], but a centralized load dependent bias function was not incorporated. Traffic rates as load was studied in [10], although biasing was not used as a means to associate users.

In addition to a changing bias value, the association order is also a critical factor when implementing dynamic CRE. While a constant bias is invariant towards which potential users are associated first, a dynamic bias requires an association order due to the changing effective cell radius. For example, associating farthest possible users first may lead to different results than associating closest users first.

The contributions of our paper are as follows:

- We propose a load dependent dynamic bias function and study its benefits over a constant bias in the HetNet downlink with and without a pico user quality of service (QoS).
- We investigate different association orders for dynamic biasing, namely outwards-only and inwards-only, and show that inwards-only associates more users, while outwards-only results in larger sum rate and average pico user performance.
- We derive equivalent static biases and radii for dynamic biasing for both association orders, hence providing an alternative method to empirically determining suitable bias values.

Since neither load dependent dynamic bias functions nor association order have received considerable attention in literature in the context of user association [1], we believe that our work provides significant insight into these concepts.

II. System Model

We consider a region with one macro BS and $K-1$ picos, with M users uniformly distributed throughout. Users are associated according to the max signal-to-interference-plus-noise (SINR) rule, which is particularly suited to biasing [8]. Users are associated to a BS i if

$$x_{i,j} = \begin{cases} 1 & \text{if } i = \underset{i}{\text{argmax}} \ \beta_i \gamma_{i,j} \\ 0 & \text{otherwise} \end{cases} \tag{1}$$

where β_i is the bias value for BS i and $\gamma_{i,j}$ is the SINR at user j from base station i, defined to be

$$\gamma_{i,j} = \frac{P_i |h_{i,j}|^2}{\sum_{k \neq i} P_k |h_{k,j}|^2 + \sigma^2}. \tag{2}$$

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Here, P_i is the transmit power from BS i, $|h_{i,j}|^2$ is the Rayleigh fading channel gain from BS i to user j with pathloss incorporated (loss exponent denoted by α), and σ^2 is the additive white Gaussian noise power. We assume the macro has no bias.

The rate achieved by user j associated with BS i is load dependent, i.e.,

$$r_{i,j} = \frac{1}{M_i} \log_2(1 + \gamma_{i,j}), \quad (3)$$

where M_i is the number of users also served by the same BS on the same subchannel. We have assumed that round robin scheduling is used, due to its proven optimality [8]. Therefore, due to the rate expression's load dependence, user association is a delicate balancing act between associating users to relieve overloading of base stations but also providing the best service. Our primary performance metric is sum rate, given by

$$\sum_{i=1}^{K}\sum_{j=1}^{M} x_{i,j} r_{i,j}. \quad (4)$$

For simplicity and investigative purposes, we define load in our paper to be the number of users associated with a BS.

III. Dynamic Bias Function

We propose a dynamic bias function that uses a different bias value depending on the number of users already associated with a particular cell. When a cell has few users, a larger bias is used, while if a cell already has a high load, a small or no bias value is used. In essence, dynamic biasing serves as a natural prevention of overloading.

We desire the bias function to decrease slowly with increasing users under low load, then asymptotically approach 0 at high load, resulting in a reverse 'S' or sigmoid shape function. This behaviour has been observed in [5] with the bias value dependent on the traffic arrival rate, and thus we feel is the most suitable shape for our function. For our work we choose to focus on the logistical function.

A. Logistical function

The flipped and shifted logistical function is shown in Fig. 1. Three important parameters of the logistical function are A, N_0, and K, where A is the asymptotic maximum value, N_0 is the location of the point of inflection, K is a parameter that controls the steepness of the curve. A dynamic bias function in terms of the number of associated users n can be defined as

$$\beta_i = B(n) = A - \frac{A}{1 + e^{-K(n-N_0)}}. \quad (5)$$

If the parameters A, K and N_0 are chosen suitably, specific functions can be obtained. For instance, setting $K = 0$ will give a constant value at $A/2$, while $K = \infty$ gives a step function with values A and 0.

The integral of the bias function gives an indication of its user capturing potential, and provides a comparative upper bound on the number of users associated. Fortunately, $B(n)$ has a closed form definite integral:

$$\int_0^N B(n)dn = AN - \frac{A}{K} \ln\left(\frac{(1 + e^{K(N-N_0)})}{(1 + e^{-KN_0})}\right). \quad (6)$$

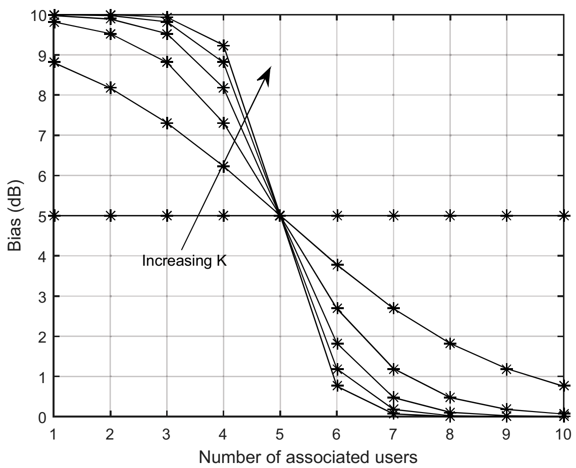

Fig. 1: Logistical bias function with varying steepness $K = \{0, 0.5, 1, 1.5, 2, 2.5\}$. $A = 10$ dB and $N_0 = 5$ for all functions.

We can confirm that (6) $\approx AN/2$ if $N_0 = N/2$, meaning that comparing a dynamic bias function with $N_0 = N/2$ and maximum value A with a constant bias of $A/2$ is a fair comparison as they have similar capturing potential.

B. Dynamic biasing and QoS

The study of the potential benefits of dynamic biasing requires consideration of whether a pico QoS, defined to be a minimum rate to be experienced by all pico users, exists, as well as a fair comparison with suitable constant bias values. Due to the shape of the dynamic bias function, a fair comparison with a constant bias would require a logical choice of the constant value. There are two obvious choices for the constant bias value - the maximum dynamic bias value (i.e., A), or the average dynamic bias value (i.e., $A/2$). There are four comparative scenarios:

No QoS, max constant bias: If there are many users to be associated, dynamic biasing would prevent a pico from being overloaded, while the constant bias will keep associating users until all users were associated to a cell. Therefore, dynamic biasing would lead to a higher average pico rate.

No QoS, average constant bias: For dense user deployments, this would have the same benefits as the above scenario but slightly smaller improvements.

QoS, max constant bias: Using a dynamic bias here would associate fewer users than a constant bias, and hence achieve a higher average pico user rate. However, the same effect could be achieved if a lower constant bias is used.

QoS, average constant bias: The same number of users may be associated for both dynamic and constant biasing, but dynamically biased users may have lower average rates as some users may be further away or suffer more interference if they were associated when the bias was high initially.

In light of this, we hypothesize that dynamic biasing is most beneficial if a pico QoS is not implemented, as a QoS would limit the advantages of a dynamic bias function by directly imposing a limit on the number of associated users and reduce overloading.

IV. Association Order

With a constant bias and no QoS, the effective cell coverage area also remains constant, and thus users can be associated in any order or at the same time. Since a dynamic bias results in changing effective cell coverage areas, the order of associating users becomes important for loading considerations as some associated users using one order may miss out if a different order is used. We define the following two association orders:

1) Outwards-only: Closest users to a pico are associated first, followed by the next closest, and so on.

2) Inwards-only: Farthest users possible are associated first, followed by the next farthest, and so on.

We hypothesize that generally, with no QoS, inwards-only leads to more users associated with a pico than outwards-only. This will be proved in the coming subsection.

Importantly, we note that inwards-only generally increases the number of associated users compared to outwards-only, not necessarily increasing the overall sum rate, average pico rate or other metric. For example, an outwards-only association may improve the average pico user rate as associated users would generally be closer to the pico than some of those associated from inwards-only.

If however a QoS is imposed, outwards-only should lead to a better rate performance for both constant and dynamic bias as associated users would be closer to the pico than if inwards-only was used.

A. Equivalent Radius

Implementing a dynamic bias will ultimately associate a certain number of users, but this may be alternatively achieved if a specific static bias is used. This also implies that a dynamic bias will result in an equivalent cell radius that corresponds to that static bias. Importantly, we note that these notions of an equivalent bias and radius are approximations and are not perfect implementation substitutes, as they rely on assuming that other base stations are arbitrarily far away.

We can obtain the equivalent cell radius for a given N (number of associated users at which the dynamic bias value is arbitrarily close to 0 dB) and user density λ, and hence show that inwards-only association associates more users than outwards-only. Suppose that a picocell with no biasing has an effective radius of r_0. For outwards-only association, if the last user associated with dynamic biasing (the Nth user) is located outside r_0, this suggests that there must be less than N users initially located within r_0. If the distance of the Nth user to the picocell is r, then the user density is

$$\lambda = \frac{N}{\pi r^2}, \tag{7}$$

meaning that the equivalent radius of the dynamic bias is

$$r = \sqrt{\frac{N}{\pi\lambda}}. \tag{8}$$

From [5], the equivalent static bias for this radius is then

$$\beta_{out} = \left(\frac{1}{r_0}\sqrt{\frac{N}{\pi\lambda}}\right)^{\alpha}. \tag{9}$$

For inwards-only, N users outside of r_0 would be associated first before those inside r_0 are associated. Thus, there must be N users located in a disc-region outside of r_0, i.e.

$$\lambda = \frac{N}{\pi(r^2 - r_0^2)}, \tag{10}$$

leading to

$$r = \sqrt{\frac{N}{\pi\lambda} + r_0^2}. \tag{11}$$

The equivalent bias is

$$\beta_{in} = \left(\frac{1}{r_0}\sqrt{\frac{N}{\pi\lambda} + r_0^2}\right)^{\alpha}. \tag{12}$$

By comparing the equivalent radii of outwards-only (8) with inwards-only (11), we can see that inwards-only will have a larger region of influence, and therefore for the same user density should associate more users.

We observe that the equivalent biases are independent of the exact shape of the bias function, i.e., independent of A and k. This is because the equivalent bias only depends on N, and not the rate at which those N users are associated.

B. Association Probability

Using the equivalent static biases derived in (9) and (12), we can also determine the association probability of a typical user associating with a tier-k base station [11]:

$$A_k = \frac{\lambda_k (P_k \beta_k)^{\frac{2}{\alpha}}}{\sum_j^K \lambda_j (P_j \beta_j)^{\frac{2}{\alpha}}} = \left(\sum_{j \neq k}^{K} \lambda_{jk} (P_{jk}\beta_{jk})^{\frac{2}{\alpha}}\right)^{-1}, \tag{13}$$

where λ_k is the k-tier base station distribution intensity, $\beta_{jk} \triangleq \beta_j/\beta_k$ and $\lambda_{jk} \triangleq \lambda_j/\lambda_k$. Replacing for β_j, β_k with either (9) or (12) will give us the association probabilities using outwards-only and inwards-only association respectively.

V. Simulation Results and Discussion

We simulate a 1000 m by 1000 m area with 100 users uniformly distributed within. A macro BS is located in the center, with a picocell 250 m away. We model pathloss as d^{-4} where d is the distance between a user and its associated BS. We set the bandwidth to 20 MHz and noise power to -174 dBm/Hz. We assume that the macro and pico share resources and hence interference is present at all users with no interference coordination strategies. Firstly, we simulate scenarios without a pico QoS, then with QoS, imposing a 1 Mb/sec minimum rate for pico users in the latter case.

As there are multiple parameters that can affect the shape of the dynamic bias function, we choose to set $K = 1$ and $N_0 = 10$ while varying the maximum dynamic bias value $A = \{3, 6, 8, 10, 13, 16\}$ dB. We have chosen this range of values for A as the represent typical pico bias values [3]. For a fair comparison, we set the constant bias to be equal to the average bias value of the dynamic bias function, i.e., constant bias is 3 dB lower than the maximum dynamic bias value.

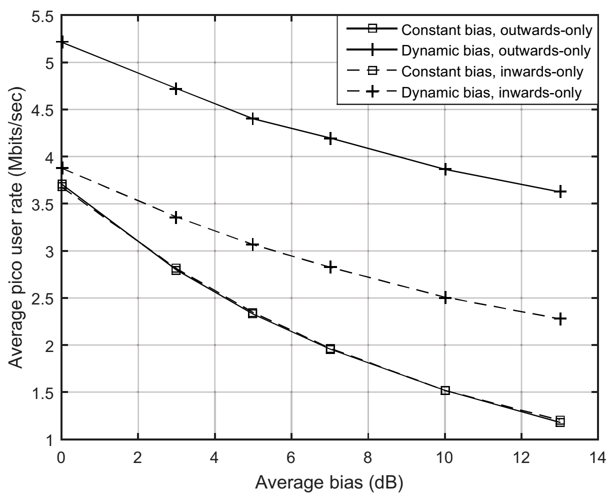

Fig. 2: Average pico user rate (no pico QoS).

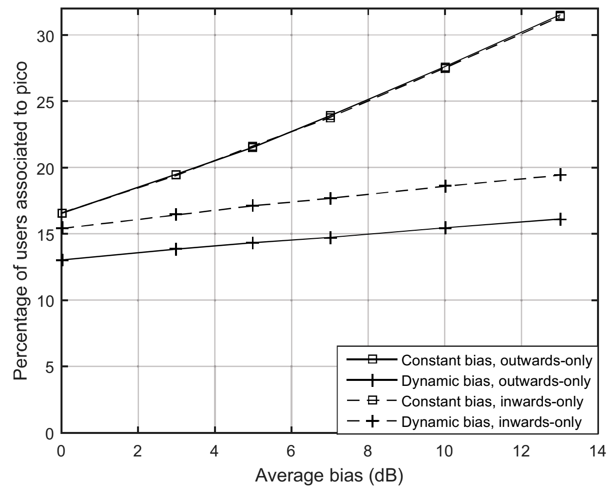

Fig. 3: Percentage of users associated with the pico (no pico QoS).

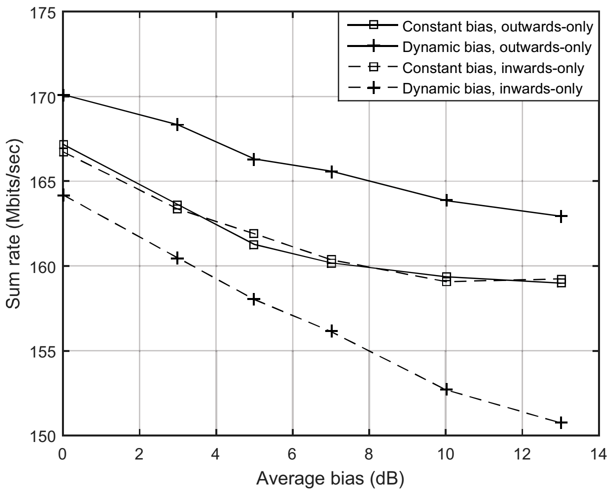

Fig. 4: Sum rate performance (no pico QoS).

TABLE I: Dynamic versus constant biasing with no pico user QoS.

No QoS	Outwards-only	Inwards-only
Average pico rate	Dynamic $>$Constant	Dynamic $>$Constant
Percentage of users associated to pico	Dynamic $<$Constant. Rate of increase slower for dynamic than for constant biasing	Dynamic $<$Constant. Larger percentage than outwards-only
Sum rate	Dynamic $>$Constant	Dynamic $<$Constant

A. No QoS

Figs.2, 3 and 4 plot the average bias versus the average pico user rate, pico user association percentage and sum rate respectively with no QoS for pico users. We observe the most benefits of using a dynamic bias over a constant bias when there is no QoS for pico users. Both outwards-only and inwards-only association leads to a higher average pico user rate in Fig. 2 than constant biasing as the falling bias values naturally prevents overloading. As expected, constant biasing has the same performance regardless of association order if there is no QoS. The rate at which users are associated with increasing max bias value A is also slower than constant biasing (Fig. 3). Further, confirming our analysis from Section IV-A, inwards-only associates more users than outwards-only, but has a lower average pico rate.

In terms of sum rate, Fig. 4 shows that dynamic biasing with outwards-only results in larger sum rate than constant biasing, but inwards-only gives a lower sum rate. This observation can be explained by the fact that inwards-only may leave users closer to the pico having to associate with the macro if it had already captured too many users, and therefore those users will experience higher interference from the pico.

The performance of constant bias is the same for outwards-only and inwards-only with no pico QoS as all users satisfying the biased association condition in (1) will be associated to the pico regardless of which order they are associated in. However, for dynamic biasing, in terms of rate performance outwards-only is more favorable than inwards-only.

A summary of results with no QoS is provided in Table I.

B. QoS

If there exists a QoS for pico users, association order affects constant biasing performance also. Figs.5, 6 and 7 plot the average bias versus the average pico user rate, pico user association percentage and sum rate respectively with a QoS for pico users. Dynamic biasing still provides a higher average pico user rate (Fig. 5) and associates fewer users (Fig. 6) than constant biasing for both outwards-only and inwards-only. Dynamic biasing also only slightly outperforms constant biasing for sum rate (Fig. 7) if outwards-only is used, while it performs worse if inwards-only is used. Thus, although we observe mostly the same benefits of dynamic over constant biasing for both association orders, under QoS the improvements are less significant and in fact approach one another for larger bias values.

A summary of results with QoS is provided in Table II.

C. Discussion

The aim of a dynamic bias is to pick the best bias at any given load for a small cell, and therefore we expect a larger bias for low load, and a smaller bias for high load. However, although the tail end of a dynamic bias function is designed to prevent overloading, its benefit is somewhat nullified since even with a constant bias, some users satisfying the biased criteria would have already been associated. For instance, a

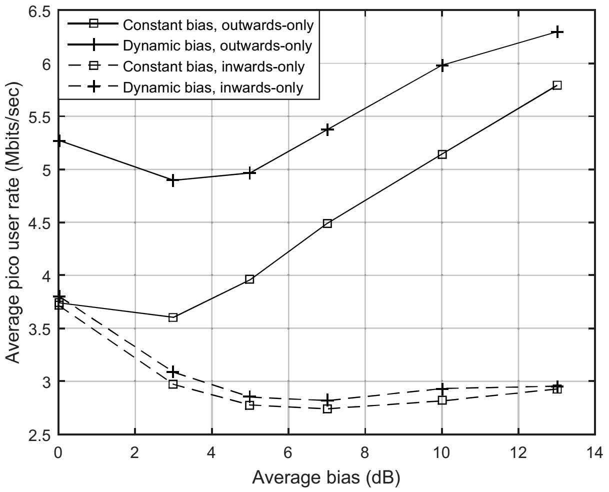

Fig. 5: Average pico user rate with pico QoS.

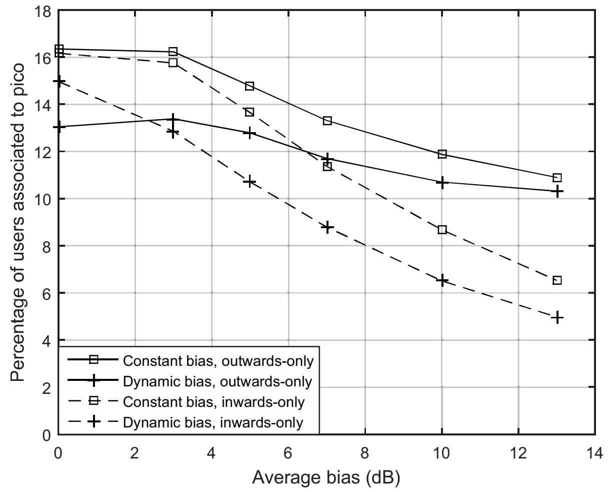

Fig. 6: Percentage of users associated with the pico with pico QoS.

bias of 4 dB will associate all users with a bias of 3 dB, meaning that if there are no users in between the biased values, then a bias of 4 dB will have the same effect as a bias of 3 dB. A QoS constraint will further limit the benefits of a dynamic bias as it is an artificial overload prevention, hence the converging performances seen in Figs. 5 to 7.

VI. Conclusion

We have studied the effects of a load dependent dynamic bias function compared to a constant bias value for cell range expansion. We have proposed a logistical function with two association orders, outwards-only and inwards-only, and found that under no pico QoS constraints, dynamic biasing with either association order leads to higher average pico rate and total sum rate with the exception of a lower sum rate when inwards-only is used. If pico QoS constraints are in place, the same improvements exist but the performances of dynamic and constant biasing are convergent with larger average bias values. We conclude that dynamic biasing with outwards-only association acts as a suitable natural prevention to pico overloading and can improve overall sum rate.

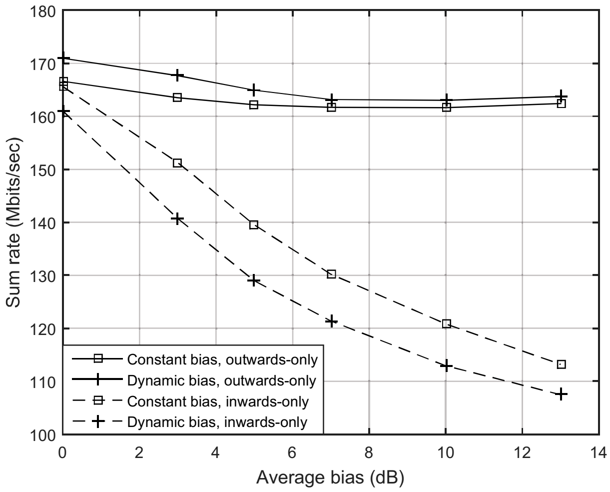

Fig. 7: Sum rate with pico QoS.

TABLE II: Dynamic versus constant biasing with pico user QoS.

QoS	Outwards-only	Inwards-only
Average pico rate	Dynamic >Constant	Dynamic >Constant Improvement less than outwards-only
Percentage of users associated to pico	Dynamic <Constant	Dynamic <Constant.
Sum rate	Dynamic >Constant	Dynamic <Constant

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