Meta-heuristic approaches to resource scheduling in heterogeneous wireless communication networks

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Abstract

An increasing demand on cellular wireless networks has targeted the heterogeneous network (HetNet) as an encouraging solution, despite unresolved issues. HetNet deploys small picocells in the coverage of a single macro base station to provide additional wireless access. Because picocells and macrocells transmit and receive signals at the same frequency, co-channel interference becomes an issue. However, a focus on minimizing interference starves certain users of resources and decreases fairness. We provide a user selection algorithm for zero-forcing beamforming (ZFBF) that maximizes number of users given constraints for power and signal-to-interference-plus-noise ratio (SINR). We construct the user selection criteria, norm and orthogonality (NO) and pathloss reciprocal (PR). Using a hill climbing algorithm, we find that the optimal weights for each criteria is 0.5. Performance analysis shows that, given several SINR thresholds, our user selection algorithm outperforms norm-based, angle-based and random user selection algorithms. Finally, we propose a weighting and priority selection method to prevent fairness violations.

Background

Physical Model

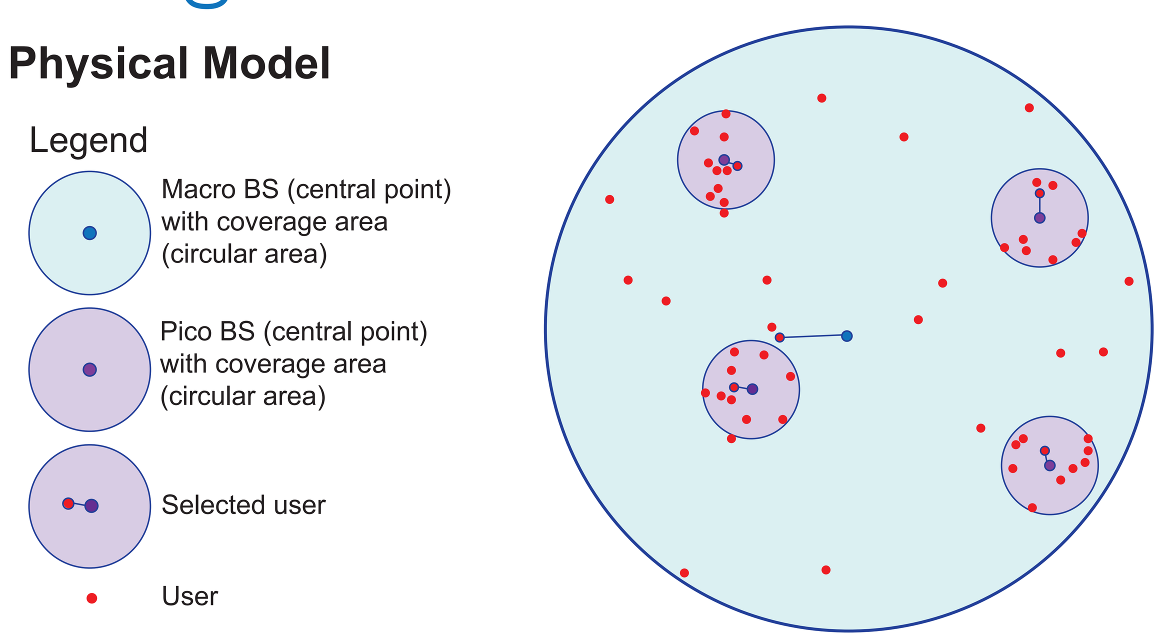

FIGURE 1. The physical model used for the simulation includes a total of 60 users, 1 macro BS with a 250 meter radius, 4 pico BS with 40 meter radii. 2/3 of the users are allocated to pico coverage areas such that there are 10 users per pico BS. The placement of pico BS and users is random.

System Model

In a heterogeneous network (HetNet) system, if X_0 and X_j denote transmited vectors from macro and pico BS, $H_{0,k}$ and $H_{j,k}$ denote channel matrices, then the signal received by the k-th user from the m-th BS would be

$$\mathbf{Y}_k = \sum_{m=0}^{M} \mathbf{H}_{m,k}\mathbf{X}_m + \mathbf{n}$$

In practical transmissions, signals are precoded and decoded to direct signals

$$\mathbf{X} \longrightarrow \mathbf{PX} \longrightarrow \mathbf{HPX} \longrightarrow \mathbf{HPX} + \mathbf{n} \longrightarrow \mathbf{W}^{\dagger}(\mathbf{HPX} + \mathbf{n})$$

X : original message
H : channel matrix, approximates fading effects
n : complex Gaussian noise
W : decoding matrix
$\dagger$: Hermitian operator
P : precoding matrix, generated by zero-forcing beamforming (ZFBF) where D, a diagonal matrix with diagonal elements d_k, keeps transmitted power constant after beamforming.

$$\mathbf{P} = \mathbf{H}^{\dagger}(\mathbf{H}\mathbf{H}^{\dagger})^{-1}\mathbf{D} \qquad d_k = \frac{1}{\sqrt{\left[(\mathbf{H}\mathbf{H}^{\dagger})^{-1}\right]_{k,k}}}$$

Signal-to-Interference-Plus-Noise Ratio (SINR)

The signal-to-interference-plus-noise ratio (SINR) for user k describes the quality of service in the system. SINR depends on BS power constraints P and the effective received power $R_{m,k}$. ZFBF simplifies SINR to

$$SINR_k = \frac{\textit{Information}}{\textit{Interference + Noise}} = \frac{|\mathbf{H}_{m,k}\mathbf{P}_{m,k}|^2 R_{m,k}}{\sum_{n\neq m}\sum_{i\in\mathcal{A}_n}|\mathbf{H}_{m,k}\mathbf{P}_{n,i}|^2 R_{n,i} + q_{m,k}}$$

where i, k are the index of the users; m,n are the index of base stations; $\mathcal{A}$-subscript is the active user group associated to a given indexed base station; q is the thermal noise randomly generated under a complex Gaussian distribution.

Methods

Ranking System

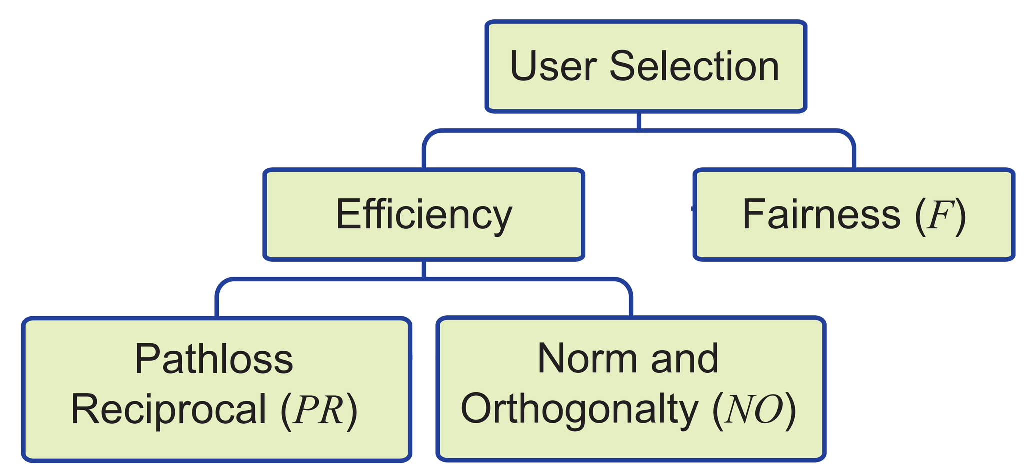

FIGURE 2. The user selection ranking system involves two components: fairness and efficiency, which depends on norm and orthogonality, and pathloss reciprocal. Weights PR, NO, F are constructed for user selection.

Simulation Process

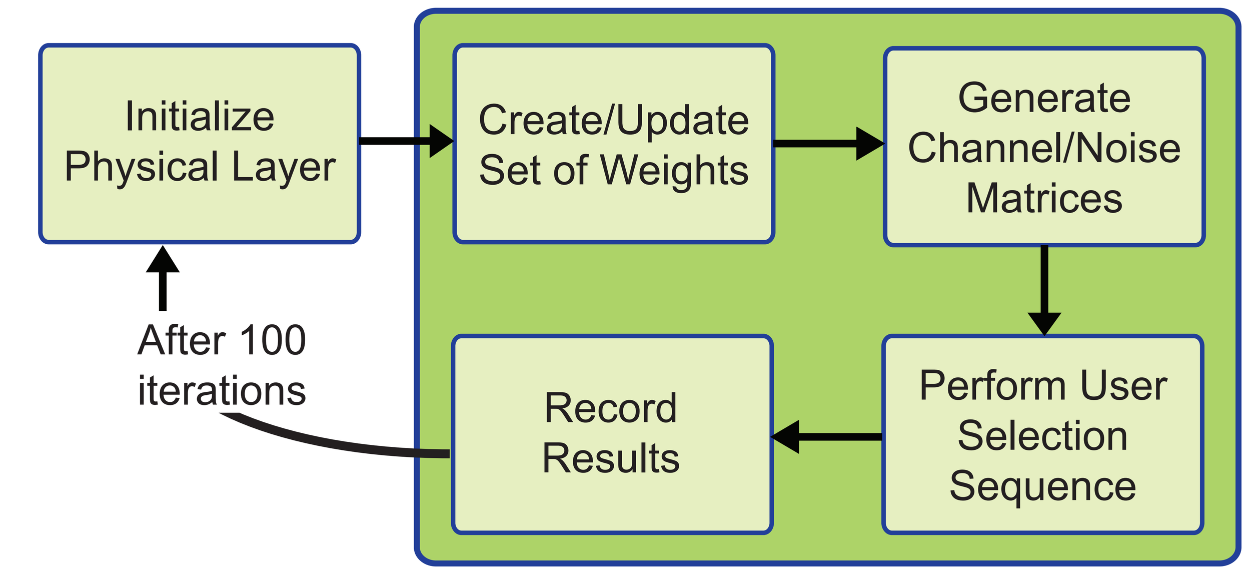

FIGURE 3. A hill climber algorithm finds the optimal PR and NO weights such that the number of users is maximized given $SINR$ and power constraints. A bidding process determines user-BS association.

Ranking Formula

Suppose $A = \{X_i\}$ is the active user group. Then the ranking function is

$$R_k : 2^A \to \mathbb{R} \qquad R_k = \omega_{NO} NO_k + \omega_{PR} PR_k$$

for user k. ω_{NO} and ω_{PR} are constant weights for the standardized norm and orthogonality score NO and the standardized pathloss reciprocal score PR, respectively. Note that $\omega_{NO} + \omega_{PR} = 1$.

One user at a time will be added to the selected group of users, $S \subseteq A$, making the ranking function

$$R_S : A \to \mathbb{R} \qquad X_i \mapsto R(S \cup \{X_i\})$$

Pathloss Reciprocal (PR)

Pathloss (PL) is the result of signal attenuation, the loss in electromagnetic wave intensity due to environmental factors. The Third Generation Partnership Project (3GPP) specifications list PL equations with r the kilometers between the user k to macro m or pico p BS

$$PL_{k,m} = 128.1 + 37.6(\log_{10} r_{k,m})$$
$$PL_{k,p} = 140.7 + 36.7(\log_{10} r_{k,p})$$

During transmission, there is a disparity between power allocated evenly to each user δ_k and the effective received power R due to PL

$$P_i = \sum_{k\in S_i} \delta_{k,i} \qquad \delta_{k,i} = \frac{P_i}{|S_i|} \qquad R_{k,i} = \frac{\delta_{k,i}}{PL_{k,i}}$$

where P_i is the maximum transmission power limitations of some indexed BS (P_m = 46 dBm, P_p = 30 dBm, dBm=decibel milliwatts), and S_i-subscript is the selected user group for some indexed BS.

$SINR$ is proportional to R and inversely proportional to PL. Define Pathloss Reciprocal (PR) as

$$PR : A \to \mathbb{R} \qquad x_i \mapsto \frac{1}{PL(x_i)}$$

With the minimum distance from user to BS set at 5 meters and the maximum distance from user to macro and pico BS set at 250 meters and 40 meters, respectively, PR is standardized and set in decibels (dB)

For macro BS, $StandPR(X_i) = 1.4392 \times 10^{6} PR(X_i) - 4.0914 \times 10^{-5}$
For pico BS, $StandPR(X_i) = 4.2211 \times 10^{7} PR(X_i) - 4.8514 \times 10^{-2}$

$StandPR$ is simply abbreviated as PR in the ranking formula.

Norm and Orthogonality (NO)

The norm and orthogonality (NO) of channel vector H determine signal quality and $SINR$. The norm of a user's vector is signal strength and the angle of users' channel vectors describes the interference between users.

Ideal user selection which increases $SINR$ satisfies the following properties

1. Each user has a large norm of their corresponding channel vectors
2. The users' channel vectors are mutually orthogonal

Suppose a BS has N antennae and K active users. The channel matrix $H \in M_{K\times N}(\mathbb{C})$ has entries that follow the complex Gaussian distribution

$$\begin{array}{cc} & \text{Antenna} \\ & \begin{array}{cccc} 1 & 2 & \dots & N \end{array} \\ H = & \begin{pmatrix} h_{1,1} & h_{1,2} & \cdots & h_{1,N} \\ h_{2,1} & h_{2,2} & \cdots & h_{2,N} \\ \cdots & \cdots & \cdots & \cdots \\ h_{K,1} & h_{K,2} & \cdots & h_{K,N} \end{pmatrix} \end{array} \begin{array}{l} \text{User } 1\text{'s Channel Vector} \\ \text{User } 2\text{'s Channel Vector} \\ \vdots \\ \text{User } N\text{'s Channel Vector} \end{array} = \begin{pmatrix} v_1^t \\ v_2^t \\ \cdots \\ v_K^t \end{pmatrix}$$

where $v_i^t \in M_{1\times N}(\mathbb{C})$ is the i-th user's channel vector. User channels can be assembled in complex vector space $\mathbb{C}^N$ as $V = \mathrm{Span}\{v_i\}_{1\leqslant i\leqslant K}$.

For V, a user's vector $v \in V$ and $v \in V - \mathrm{Span}S$. $\mathscr{B} = \{v_1, v_2, \cdots, v_n\}$ is a basis. A is a set of all users' channel vectors, $S = \{v_i\}_{i\in\mathcal{I}}$ where $S \subseteq A$. e_i is a unit vector in the space:

$$Null(v_i) := \mathrm{Span}(\mathscr{B} - \{v_i\} = \{v \in V : (v, v_j) = 0, \forall j \neq i\}$$

Define $NO_S : S \to \mathbb{R}$, the norm and orthogonality of vector v_i with respect to the set S to be

$$NO_S(v_i) := ||v_i||_2 \cos(\theta(v_i, W))$$

Further define NO of set S to be a function

$$NO : 2^A \to \mathbb{R} \qquad S \mapsto \sum_{v_i\in S} NO_S(v_i)$$

To standardize NO, using the fact that channel matrix entries follow the complex Gaussian distribution and computing the expected value of the norm results in

$$StandNO(S) = \frac{25\sqrt{\pi}}{4} NO(S)$$

$StandNO$ is simply abbreviated as NO in the ranking formula.

Fairness (F)

A basic principle in fairness scheduling is to guarantee that all active users will be served within a certain time period. We intend to establish a fairness function

$$F : \text{User} \times \text{Time} \to \mathbb{R}$$

and incorporate it into our ranking formula for the n-th user

$$R_n = F_n \times (\omega_{NO} NO_n + \omega_{PR} PR_n)$$

Axioms of F function

$F(n,t)$ is the fairness function for user n at time t. F should satisfy the following axioms:

1. $F(n,t) \geq 1, \forall n, t$.
2. $F(n,t)$ is piece-wisely increasing w.r.t t.
3. There is a fixed number T such that for any n, if $F(n,t_1) = F(n,t_2) = 1$ and $F(n,t) > 1$ for $t_1 < t < t_2$, then $t_2 - t_1 < T$.
4. For any n, if $F(n,t+1) \leq F(n,t)$, then $F(n,t) = 1$.

Priority Selection

To ensure that unserved users do not exceed the capacity of the transmitters

N : total number of active users in the system
n : average number of users served at each period
T : period of time
k : priority selection size, depends on simulation in our model - (high efficiency) $1 \leq k \leq 3$ (guaranteed fairness)

$$N = (T \times k) + (n - k)$$
$$k = \frac{N - n}{T - 1}$$

Results

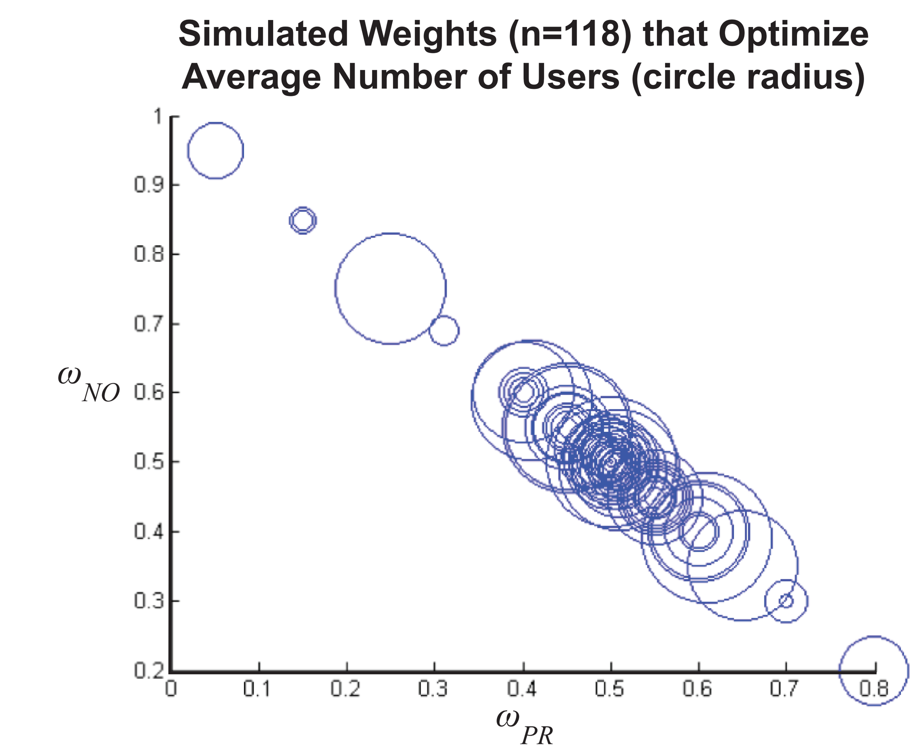

FIGURE 4. The hill climber simulation ran n=118 times. For each trial, a solution for the weights ω_{NO} and ω_{PR} was found that maximized the average number of users, given power and $SINR$ constraints. The radius of a circle represents the average number of users for that trial's solution weights. The 118 solutions converged to $\omega_{NO} = \omega_{PR} = 0.50$.

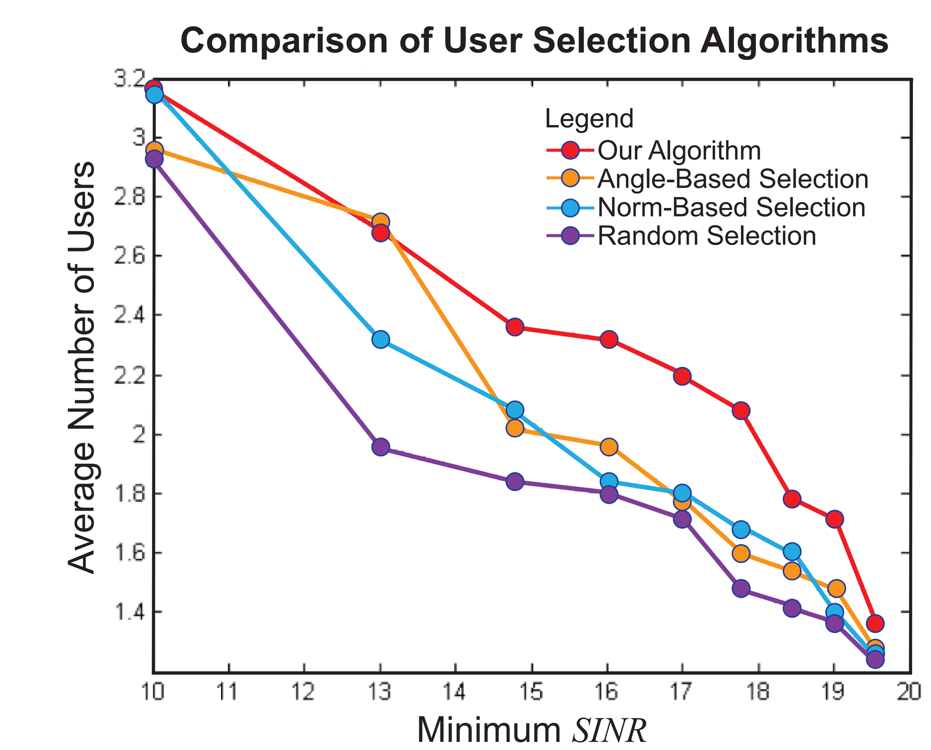

FIGURE 5. Given varying $SINR$ constraints, the average number of users served by our user selection algorithm (top, red) compared to angle-based selection (second to the top, orange), norm-based selection (second to the bottom, blue), and random selection (bottom, violet).

Discussion

Summary

1. **Developed a mathematical user selection method to meet $SINR$ and power constraints**

   NO is an effective user selection metric which simplifies calculations by combining norm-based and angle-based measures. PR improves the efficiency of standard methods for incorporating system constraints.

2. **Demonstrated the effectiveness of our user selection method by conducting simulations**

   There exists a set of weights $\omega_{NO} = \omega_{PR}$ = 0.50 that maximizes the average number of users served given system constraints. Our user selection method, *Ranking Formula* = 0.5(NO) + 0.5(PR) outperforms norm-based, angle-based, and random selection methods.

Future Directions

1. Incorporate and test fairness in our user selection method
2. Test the scalability of our method by increasing macro BS, adding femto BS, changing the number of users
3. Use improved optimization techniques such as stochastic gradient descent and genetic algorithms
4. Use different precoding techniques such as dirty paper coding

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