On Velocity-based Association Policies for Multi-tier 5G Wireless Networks

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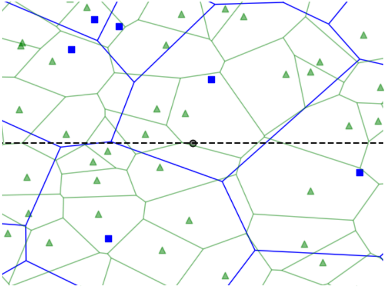
Introduction

- Beam-based communications for 5G networks: allows to concentrate energy and improve signal power
- Setup: multi-tier network involving different types of base stations (BSs) sharing the same frequency bands
- Key features: beam selection, beam switching and cell handovers may degrade the network performance
- Performance also depends on the velocity of mobile users (MUs): higher velocities lead to more frequent beam selections
-

Can we devise velocity-aware association policies for 5G networks ?

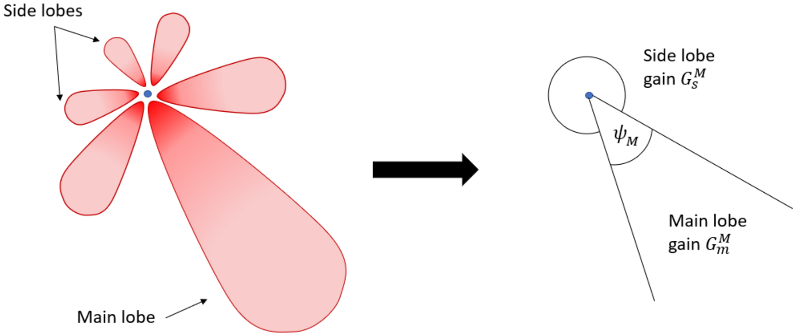
Network setup

- Two-tier downlink cellular network, with a *macro* tier and a *micro* tier
- Network in open access and MU connect to the closest BS in their association tier
- BSs distributed according to two Poisson point processes (PPPs) Φ_M and Φ_μ of intensities λ_M and λ_μ with $\lambda_\mu > \lambda_M$
- MUs are distributed according to a PPP Φ_u of intensity λ_u
- BSs are always active
- BSs create a Poisson-Voronoi (PV) tessellation of the plane
- MUs move in a straight line along the x-axis
- MU velocity i.i.d with distribution f (in simulations, $f = \mathcal{E}\left(\frac{1}{v_u}\right)$)



Beamforming and beam management

- Each BS in the macro/micro tier has respectively n_M and n_μ beams, with angular width $\psi_M = \frac{2\pi}{n_M}$ (resp. $\psi_\mu = \frac{2\pi}{n_\mu}$)
- Antenna gains: $G_m^M = n_M$ for the main lobe, $G_s^M = \frac{1}{n_M}$ for the side lobe



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- The antenna gain in the macro tier is:

$$G^M(\theta) = \begin{cases} G_m^M & \text{if } |\theta| \leq \psi_M/2 \\ G_s^M & \text{else} \end{cases}$$

- The antenna gain w.r.t. the typical user located at the origin is:

$$g_{M,x} = \begin{cases} G_m^M & \text{w.p.} \quad p_{M,m} \equiv \frac{\psi_M}{2\pi} = \frac{1}{n_M} \\ G_s^M & \text{w.p.} \quad 1 - p_{M,m} \end{cases}$$

Beam reselection and cell handover

- When a MU crosses a beam boundary, beam reselection happens. Time intensity of beam boundary crossings along a line (cf Theorem 2 of [?]):

$$\nu_{M,b} = \frac{n_M \sqrt{\lambda_M}}{\pi} v$$

- Beam selection happen during synchronization signal block (SSB) with periodicity τ. The effective time intensity of beam reselections is equal to:

$$\nu_{M,e} = \min\left(\frac{1}{\tau}, \nu_{M,b}\right)$$

- When a MU crosses a cell boundary, a cell handover happens. If the MU moves at velocity v, the time intensity of cell handovers is equal to:

$$\nu_{M,c} = \frac{4\sqrt{\lambda_M}}{\pi} v$$

- The overhead per unit of time is defined as:

$$T_o^M = \nu_{M,c} T_{M,c} + \nu_{M,e} T_{M,b}$$

Mobility-induced beam misalignment

- Beam misalignment: happens if a MU moves out of its reference beam between two SSBs without reselecting a new beam. Spatial intensity of beam boundary crossing along a straight line:

$$\mu_{s,b} = \frac{n_M \sqrt{\lambda_M}}{\pi}$$

- Beam misalignment for a MU moving at velocity v happens with probability:

$$p_{\mathrm{bm}}^{M}(v) = 1 - \exp\left(-v \mu_{M,b} \tau\right)$$

- The antenna gain at the serving BS of the typical MU located at the origin is:

$$g_{M,0} = \begin{cases} G_m^M & \text{w.p.} \quad 1 - p_{\mathrm{bm}}^{M}(v) \\ G_s^M & \text{w.p.} \quad p_{\mathrm{bm}}^{M}(v) \end{cases}$$

Access Policy and SINR

- Path-loss function: $\ell(x) \triangleq Kx^{-\alpha}$, with $\alpha > 2$ and $K = \left(\frac{c}{4\pi f_c}\right)^2$
- Transmit powers $P_M \geq P_\mu$ and thermal noise power σ^2
- We assume Rayleigh fading h_x for a BS located at x with power 1
- Interference experienced by the typical MU located at the origin associated with the macro tier:

$$I_M(\Phi_M) = \sum_{x \in \Phi_M} h_x g_{M,x} P_M \ell(\|x\|).$$

- SINR at the typical MU conditioned on the closest BS to the origin $X_{M,0}$ being at distance r:

$$\mathrm{SINR}_M = \frac{h_0 P_M g_{M,0} K r^{-\alpha}}{\sigma^2 + I_M(\Phi_M \setminus \{X_{M,0}\}) + I_\mu(\Phi_\mu)},$$

Coverage probability

Coverage probability at T in a tier: CDF of the SINR in this tier

Theorem (Coverage probability)

The coverage probability with the macro tier association is

$$p_M(v,T) = (1 - p_{bm}^M(v))\, q_M(G_m^M, T) + p_{bm}^M(v)\, q_M(G_s^M, T)$$

where $\delta = 2/\alpha$ *and:*

$$q_M(G,T) = \pi\lambda_M \int_{r\geq 0} e^{-\pi\lambda_M r - \frac{T\sigma^2}{P_M K G} r^{1/\delta}} \exp\left(-\pi r \left(\frac{T}{P_M G}\right)^{\delta} \left(\lambda_M P_M^{\delta} \rho_M(G,T) + \lambda_\mu P_\mu^{\delta} \kappa_\mu\right)\right) \mathrm{d}r$$

with:

$$\rho_M(G,T) = p_{M,m} (G_m^M)^{\delta} \int_{\left(\frac{TG_m^M}{G}\right)^{-\delta}}^{\infty} \frac{\mathrm{d}u}{1+u^{1/\delta}} + (1 - p_{M,m})(G_s^M)^{\delta} \int_{\left(\frac{TG_s^M}{G}\right)^{-\delta}}^{\infty} \frac{\mathrm{d}u}{1+u^{1/\delta}}$$

$$\kappa_\mu = \left(p_{\mu,m} \left(G_m^{\mu}\right)^{\delta} + (1 - p_{\mu,m}) \left(G_s^{\mu}\right)^{\delta}\right) \int_0^{\infty} \frac{\mathrm{d}u}{1+u^{1/\delta}}$$

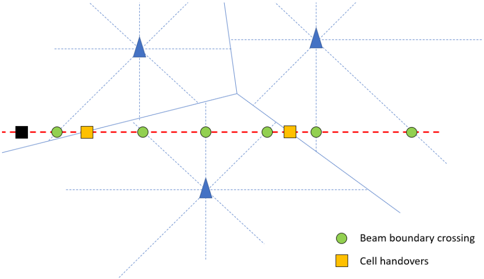
Shannon Rate and Mean Effective Shannon Rate

- The Shannon rate experienced by the typical MU located at the origin in the macro tier is equal to:

$$\mathscr{R}_M = \mathbb{E}\left[\log(1+\mathrm{SINR}_M)\right] = \int_0^{Q_{max}} \frac{p_M(T)}{T+1}\mathrm{d}T$$

- The *Mean effective Shannon rate* (MESR) by the same MU is equal to:

$$\mathscr{R}_{M,\mathrm{eff}} = \mathscr{R}_M\left(1 - T_{o,M}(v)\right)^+$$



Velocity-based association policy

Velocity-based association policy in the network: criterion $\mathscr{P}$ *only depending on velocity* such that:

- If $\mathscr{P}(v)$, the MU is associated with the micro tier
- If $\bar{\mathscr{P}}(v) = \neg\mathscr{P}(v)$, it is associated with the macro tier

The *average MESR* under a given association policy $\mathscr{P}$ is given by:

$$\mathscr{R}(\mathscr{P}) = \int_0^{\infty} \left(\mathscr{R}_{\mu,\mathrm{eff}}(v)\mathbb{1}_{\mathscr{P}(v)} + \mathscr{R}_{M,\mathrm{eff}}(v)\mathbb{1}_{\bar{\mathscr{P}}(v)}\right) f(v)\mathrm{d}v$$

Admits an ergodic interpretation (Birkhoff's ergodic theorem, [**?**])

Velocity-based Association Policy

The *threshold* policy with threshold v_T is $\mathscr{P}(v) = \mathbb{1}\{v < v_T\}$.

The average MESR under a threshold policy with threshold v_T is given by:

$$\mathscr{R}(v_T) = \int_0^{v_T} \mathscr{R}_{\mu,\text{eff}}(v) f(v) \mathrm{d}v + \int_{v_T}^{\infty} \mathscr{R}_{M,\text{eff}}(v) f(v) \mathrm{d}v$$

First step, we assume that there is only one MU per cell:

Theorem (Threshold velocity-based association policy with one user per cell)

There exists a unique threshold policy the average MESR per user. This optimal threshold $v_T^\star$ does not depend on the velocity distribution f of MUs, and is the unique solution to:

$$\mathscr{R}_{\mu,eff}(v_T^\star) = \mathscr{R}_{M,eff}(v_T^\star)$$

Optimal Threshold Policy

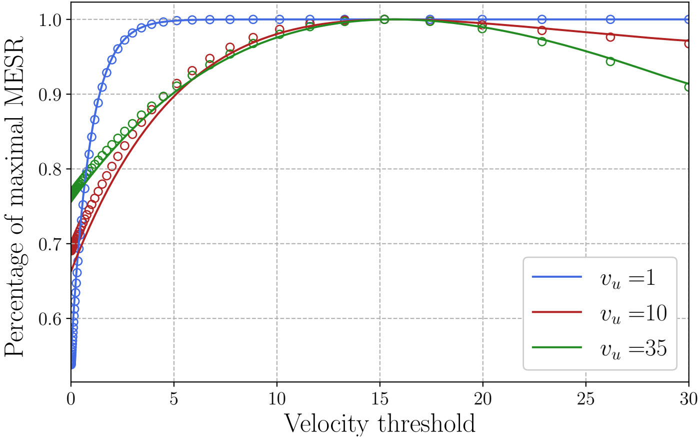


Figure: Normalized MESR in the network as a function of the velocity threshold v_T. The optimal threshold does not depend on the scale parameter v_u

Load-dependent Velocity-based Association Policies

Consider a TDMA setup where radio resources are equally shared among all users sharing the same BS. The average MESR experienced by the typical MU located at the origin under association policy $\mathscr{P}$ is now equal to:

$$\mathscr{R}_{\text{load}}(\mathscr{P}) = \mathbb{E}\left[\frac{\log(1+\text{SINR}_{0,M})(1-T_{o,M}(V))^+}{Z_\mu^0(\mathscr{P})}\mathbb{1}_{\mathscr{P}(V)}\right] + \mathbb{E}\left[\frac{\log(1+\text{SINR}_{0,\mu})(1-T_{o,\mu}(V))^+}{Z_M^0(\bar{\mathscr{P}})}\mathbb{1}_{\bar{\mathscr{P}}(V)}\right]$$

where Z_M^0 and Z_μ^0 denote the number of users in the zero-cell of the PV tessellation associated with each tier under association policy $\mathscr{P}$.

Assumption:

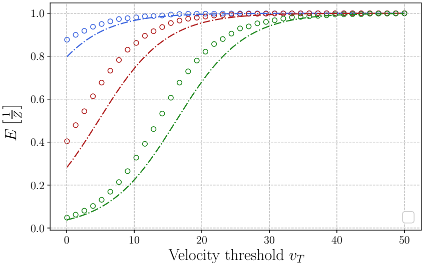
$$\hat{\mathscr{R}}_{\text{load}}(\mathscr{P}) = \mathbb{E}\left[\frac{1}{Z_\mu^0(\mathscr{P})}\right]\mathbb{E}\left[\mathscr{R}_{\mu,\text{eff}}(v)\mathbb{1}_{\mathscr{P}(v)}\right] + \mathbb{E}\left[\frac{1}{Z_M^0(\bar{\mathscr{P}})}\right]\mathbb{E}\left[\mathscr{R}_{M,\text{eff}}(v)\mathbb{1}_{\bar{\mathscr{P}}(v)}\right]$$

Population of the zero-cell

- Mus associated with the macro/micro tier form two PPP of respective intensities $\lambda_u F(v_T)$ and $\lambda_u(1-F(v_T))$
- Immediate heuristic:

$$\mathbb{E}\left[\frac{1}{Z_0^M}\right] \approx \frac{1}{\mathbb{E}[Z_0^M]} = \frac{1}{1+1.28\frac{\lambda_M}{\lambda_u F(v_T)}}$$

- Predicts poorly the value of the average inverse load in the network



Population of the zero-cell

Lemma

Let Φ and Ψ be two PPPs of respective intensities λ and ν. Let V_0 be the 0-cell of the PV tessellation associated with the process Φ and let $Z = 1 + |\Psi \cap V_0|$. Finally, let $L : x \mapsto x\left(1 - \left(\frac{1}{1+\frac{2}{7x}}\right)^{7/2}\right)$. The moment of order -1 of Z can be approximated by (see [?]):

$$\mathbb{E}\left[\frac{1}{Z}\right] \approx L\left(\frac{\lambda}{\nu}\right)$$

Under a threshold policy:

$$\mathbb{E}\left[\frac{1}{Z_\mu^0(v_T)}\right] = L\left(\frac{\lambda_\mu}{\lambda_u F(v_T)}\right) \equiv L_\mu(v_T)$$

$$\mathbb{E}\left[\frac{1}{Z_M^0(v_T)}\right] = L\left(\frac{\lambda_M}{\lambda_u (1 - F(v_T))}\right) \equiv L_M(v_T)$$

Population of the zero-cell

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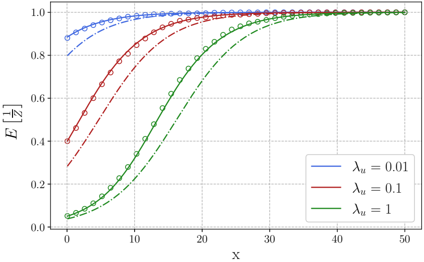
$$\mathbb{E}\left[\frac{1}{Z}\right] \approx L\left(\frac{\lambda}{\nu}\right)$$

Provides a much better approximation for the inverse load



Load-threshold heuristic

- Using the previous lemma, the heuristic for the MESR becomes:

$$\hat{\mathscr{R}}_{\text{load}}(v_T) = L_\mu(v_T) \int_0^{v_T} \mathscr{R}_{\mu,\text{eff}}(v) f(v) \mathrm{d}v + L_M(v_T) \int_{v_T}^{\infty} \mathscr{R}_{M,\text{eff}}(v) f(v) \mathrm{d}v$$

- We then define the *load-threshold* heuristic v_{LT} for the optimal MESR in the network as follows:

$$v_{\text{LT}} \triangleq \arg\max \hat{\mathscr{R}}_{\text{load}}(v_T)$$

- **Claim :** v_{LT} is uniquely defined and corresponds to a maximum of the MESR in the network.
- In the load-dependent case, v_{LT} depends on the velocity distribution f

Load-threshold heuristic

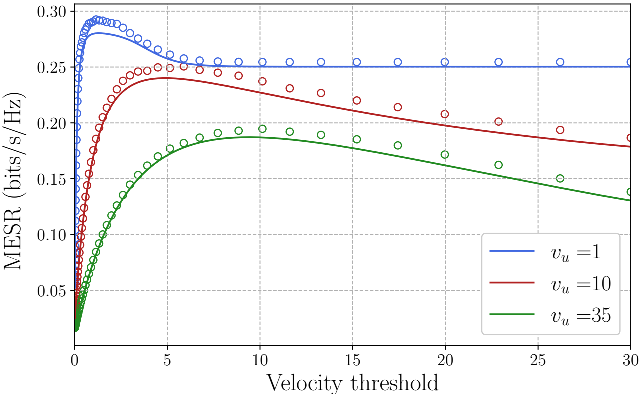


Figure: Comparison of the load-threshold heuristic (plain line) and simulations (circles) for a fixed user density $\lambda_u = 1$

Discussion - Comparison with a Classical Association Policy

Classical Association Policy: Maximum Average Received Power (MARP). Each MU connects to the tier offering the best power

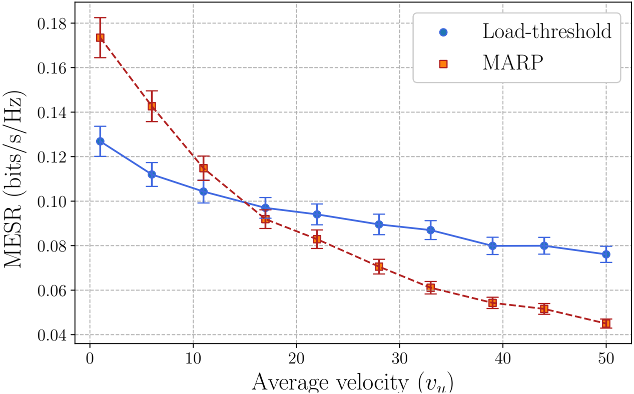


Figure: Comparison between the MARP policy (red) and the load-threshold policy under v_{LT} (blue) with 95% confidence intervals for a fixed user density $\lambda_u = 1$

Discussion - Effect of the Density of MUs in the network

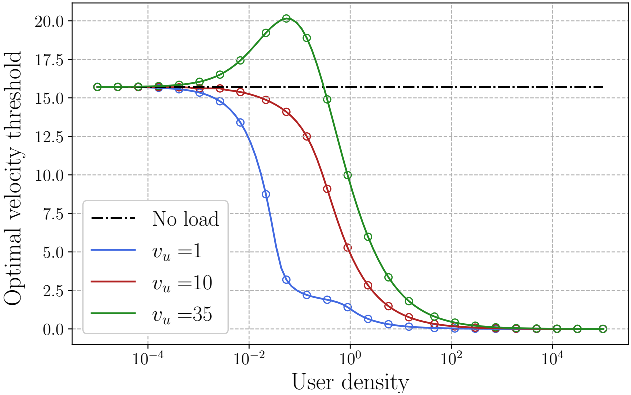


Figure: Optimal velocity threshold obtained for the load-threshold heuristic v_{LT} (in plain line) for three velocity distributions against the density of users. In black, dashed, the equivalent network without load

Extension - Maximum biased received power

MARP: connect the the macro tier if $\mathrm{RP}_M > \mathrm{RP}_\mu$. Threshold policy: connect to the macro tier if $v > v_T$

Idea: add a bias factor K depending on the velocity

Introduce K-policies: define $K : \mathbb{R}_+ \to \mathbb{R}_+$ such that:

- If $\mathrm{RP}_M > K(v)\mathrm{RP}_\mu$, we connect to the macro tier
- If $\mathrm{RP}_M < K(v)\mathrm{RP}_\mu$

MARP	Load-threshold policy
$K(v) = 1$	$K(v) = \begin{cases} 0 & \text{if } v > v_T \\ \infty & \text{else.} \end{cases}$

Extension - Maximum biased received power

Define the conditional CDF for the SINR $\mathbb{P}\left[\mathrm{SINR}_{0,M} > T \,\middle|\, |X_{0,\mu}| = s, |X_{0,M}| = r\right]$

Compute the MESR in the network according to:

$$\mathscr{R}(K) = \int_{v=0}^{\infty} \Bigg((1 - T_{o,M}(v))^{+} \int_{r=0}^{\infty} \int_{s=\left(\frac{P_\mu K(v)}{P_M}\right)^{1/\alpha} r}^{\infty} \mathbb{E}\left[\log(1+\mathrm{SINR}_{0,M})\right] e^{-\pi(\lambda_M r^2 + \lambda_\mu s^2)} 2\pi\lambda_\mu 2\pi\lambda_M \mathrm{d}s\mathrm{d}r$$

$$+ \, (1 - T_{o,\mu}(v))^{+} \int_{r=0}^{\infty} \int_{s=0}^{\left(\frac{P_\mu K(v)}{P_M}\right)^{1/\alpha} r} \mathbb{E}\left[\log(1+\mathrm{SINR}_{0,\mu})\right] e^{-\pi(\lambda_M r^2 + \lambda_\mu s^2)} 2\pi\lambda_\mu 2\pi\lambda_M \mathrm{d}s\mathrm{d}r \Bigg) f(v)\mathrm{d}v.$$

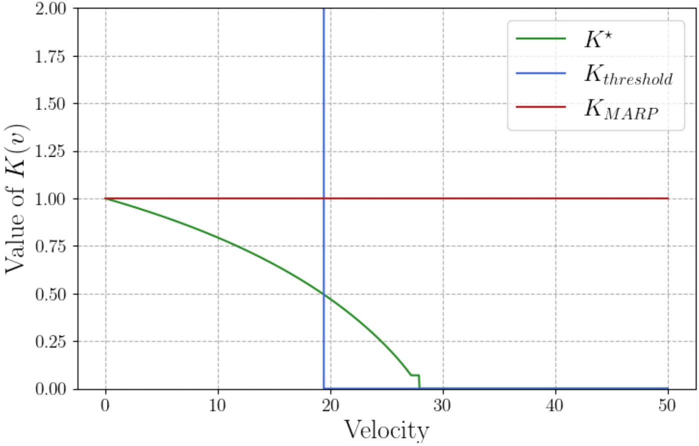
Use Euler-Lagrange's criterion to find a function $K^\star$ that maximizes the MESR:

$$\frac{\partial}{\partial K} L(v, K) = 0$$

where $\mathscr{R}(K) = \int_{v=0}^{\infty} L(v,K) f(v)\mathrm{d}v$

Extension - Maximum biased received power

Obtain an equation tying $K^\star(v)$ and v to solve numerically



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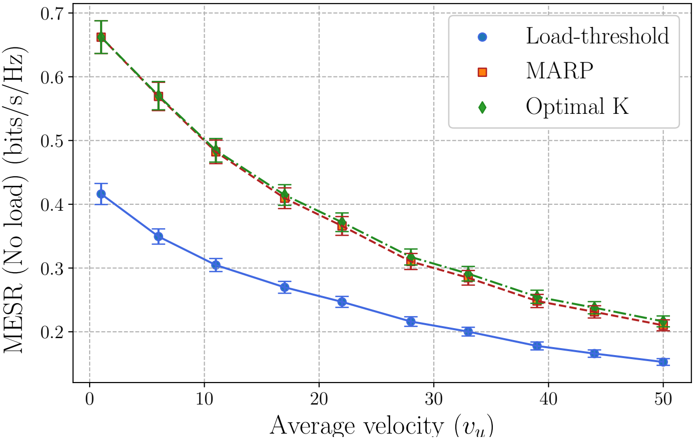

References I