Context-Aware Energy Saving with Proactive Power Allocation

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Background

Passive Resource Allocation Policy:

Based on up-to-date information of users and the network, awaiting users' initiatives.
Popular in existing cellular networks

For Energy-Saving or Other Green Communication Goals,

Proactive Resource Allocation Policy:

Strategically pre-buffers based on ignored yet predictable context information such as:

- User Service Requests
- User Future Data Rate(Channel Quality)
- Network Resources Availability
- …

Background

- Existing Work on Proactive Resource Allocation:

  Assumption: perfect prediction of future data rate

  Reduced Spectral Utilization

  Energy-Saving

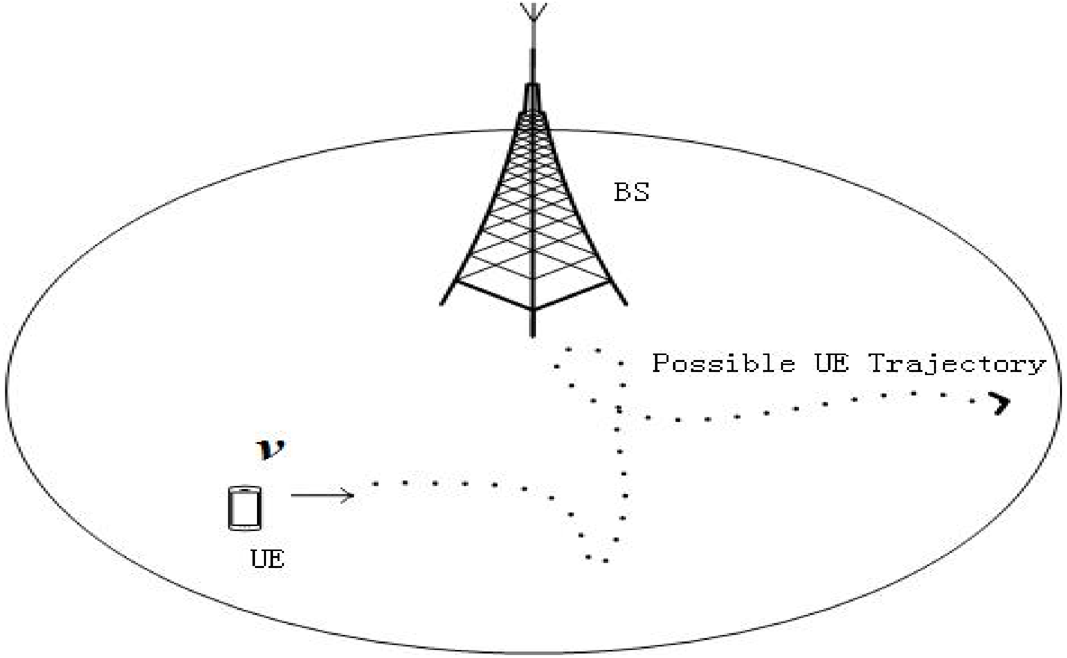
BUT small scale channel fading
future resource availability } Hard to Accurately Predict!!

- Existing Work on the Impact of Rate Prediction Uncertainty:

  Assumption: triangular membership function modelling rate uncertainty

  robust BS airtime allocation method

System Model



downlink transmission of a MISO-OFDM system

N_t antennas; K subcarriers;
subcarrier spacing Δ_f ;time slot Δ_t
Availability ξ_{nk} : i.i.d Bernoulli r.v ρ_n

Achievable data rate in the n_{th} time slot

$$R_n = \sum_{k=1}^{K} \Delta_f \cdot \xi_{nk} \log\left(1 + p_n \lambda_n \left\| \mathbf{h}_{nk} \right\|^2\right)$$

$$\lambda_n \triangleq \frac{\alpha_n}{\sigma^2}$$

Large-Scale Channel Gain

Variance of AWGN

Accumulative data within $N\Delta_t$

$$\sum_{n=1}^{N} \sum_{k=1}^{K} \Delta_f \cdot \xi_{nk} \log\left(1 + \lambda_n p_n \left\| \boldsymbol{h}_{nk} \right\|^2\right) \cdot \Delta_t$$

Problem Formulation

Minimize the average total transmit energy consumed for conveying the B bits in N time slots, under the transmission outage constraint as well as maximal transmit power constraint

$$\min_{\mathbf{p}} \ \mathbf{E}\left\{\Delta_t \sum_{n=1}^{N}\sum_{k=1}^{K} \xi_{nk} p_n\right\} = \sum_{n=1}^{N} \Delta_t K \rho_n p_n$$

$$s.t. \quad P_{out}(\mathbf{p}) = \Pr\left(\sum_{n=1}^{N}\sum_{k=1}^{K} \xi_{nk} \log\left(1+\lambda_n p_n \left\|\boldsymbol{h}_{nk}\right\|^2\right) < S\right) \le \varepsilon$$

ε → maximum acceptable outage probability

$$0 \le p_n \le \frac{P_{\max}}{K}, n = 1, \ldots, N$$

$$S \triangleq \frac{B}{\Delta_f \Delta_t}$$

B → file size

subcarrier spacing (Δ_f)

time slot length (Δ_t)

First Step: Transform the outage probability constraint into a convex constraint with explicit expression

Outage Probability Constraint

$$P_{out}(\mathbf{p}) \triangleq \Pr\left(\sum_{n=1}^{N}\sum_{k=1}^{K}\xi_{nk}\log\left(1+\lambda_n p_n \left\|\boldsymbol{h}_{nk}\right\|^2\right) < S\right)$$

$$= \Pr\left(\sum_{n=1}^{N}\sum_{k=1}^{K}\xi_{nk}\left[\log\left(\left\|\boldsymbol{h}_{nk}\right\|^2\right)+\log\left(\frac{1}{\left\|\boldsymbol{h}_{nk}\right\|^2}+\lambda_n p_n\right)\right] < S\right)$$

$$\approx \Pr\left(\sum_{n=1}^{N}\sum_{k=1}^{K}\xi_{nk}\left[\log\left(\left\|\boldsymbol{h}_{nk}\right\|^2\right)+\log\left(A+\lambda_n p_n\right)\right] < S\right)$$

Auxiliary variable to control the accuracy of the approximation

Decouple $\boldsymbol{p}_n$ and $\left\|\boldsymbol{h}_{nk}\right\|^2$ to obtain a convex constraint with explicit expression

Hierarchical Method

Step 1: Power Allocation for Given A

$$\min_{\mathbf{p}} \ \mathbf{E}\left\{\Delta_t \sum_{n=1}^{N}\sum_{k=1}^{K}\xi_{nk}p_n\right\} = \sum_{n=1}^{N}\Delta_t K\rho_n p_n$$

$$s.t. \quad \Pr\left(\sum_{n=1}^{N}\sum_{k=1}^{K}\xi_{nk}\left[\log\left(\left\|\boldsymbol{h}_{nk}\right\|^2\right)+\log\left(A+\lambda_n p_n\right)\right]<S\right)$$

$$0 \le p_n \le \frac{P_{\max}}{K}, n=1,\ldots,N$$

As each term is i.i.d, based on C.L.T,

$$R_n(A)=\sum_{k=1}^{K}\xi_{nk}\left(\log\left(\left\|\boldsymbol{h}_{nk}\right\|^2\right)+\log\left(A+\lambda_n p_n\right)\right)\sim N\left(E_n,D_n\right)$$

Considering for $n=1,\ldots,N$, $R_n(A)$ are independent from each other

$$\sum_{n=1}^{N}\sum_{k=1}^{K}\xi_{nk}\left[\log\left(\left\|\boldsymbol{h}_{nk}\right\|^2\right)+\log\left(A+\lambda_n p_n\right)\right]\sim N\left(\sum_{n=1}^{N}E_n,\sum_{n=1}^{N}D_n\right)$$

Outage probability constraint converted into a explicit expression with respect to $\boldsymbol{p}$,

$$\sqrt{\sum_{n=1}^{N}\boldsymbol{D_n}\left(p_n\right)} \le -\frac{\sum_{n=1}^{N}\boldsymbol{E_n}\left(p_n\right)}{\boldsymbol{\phi}^{-1}\left(\boldsymbol{\varepsilon}\right)}+\frac{\boldsymbol{S}}{\boldsymbol{\phi}^{-1}\left(\boldsymbol{\varepsilon}\right)}$$

Hierarchical Method

Step 1: Power Allocation for Given A

$$E_n = K\rho_n\left[\log\left(A+\lambda_n p_n\right)+\log(e)\psi\left(N_t\right)\right]$$

$$D_n = K\log^2(e)\dot{\psi}\left(N_t\right)\rho_n + K\rho_n\left(1-\rho_n\right)\cdot$$

$$\left[\log\left(A+\lambda_n p_n\right)+\log(e)\psi\left(N_t\right)\right]^2$$

Denote

$$c_n = \rho_n\left(1-\rho_n\right)$$

$$z_n = \log\left(A+\lambda_n p_n\right)+\log(e)\psi\left(N_t\right)$$

Outage probability constraint converted into a convex constraint with explicit expression:

$$\min_{\{z_n\}} \sum_{n=1}^{N}\frac{\rho_n}{\lambda_n}2^{z_n}$$

$$s.t. \sqrt{\sum_{n=1}^{N}K\left[c_n z_n^2+\log^2(e)\dot{\psi}\left(N_t\right)\rho_n\right]} \le -\frac{\sum_{n=1}^{N}K\rho_n z_n}{\phi^{-1}(\varepsilon)}+\frac{S}{\phi^{-1}(\varepsilon)}$$

Convex Concave

Hierarchical Method

Step 2: Optimization of A

The largest A whose corresponding power allocation $\boldsymbol{p}^*(\boldsymbol{A})$ ensures the original outage probability.

Largest: Average Energy Consumption is monotonically decreasing with respect to A

Method: Bisection method, extra constraint

$$P_{out}\left(\hat{\mathbf{p}}^*(A_U)\right) \leq P_{out}\left(\hat{\mathbf{p}}^*(A)\right) \leq P_{out}\left(\hat{\mathbf{p}}^*(A_L)\right)$$

Ensuring the convergence as the corresponding outage probability is monotonically increasing with A

Hierarchical Method

Step 2: Optimization of A

Numerical Expression of Outage Probability for given $\boldsymbol{p}^{*}(\boldsymbol{A})$:

$$P_{out}(\hat{\mathbf{p}}^{\star}(A)) = \Phi\left(\frac{S - \sum_{n=1}^{N} K\rho_n \hat{E}_n}{\sqrt{\sum_{n=1}^{N} K(\rho_n \hat{D}_n + \rho_n(1-\rho_n)\hat{E}_n^2)}} \right)$$

$$\hat{E}_n = \frac{\int_0^{\infty} \log(1+\hat{p}_n^{\star}(A)\lambda_n x) x^{N_t-1} e^{-x}\, \mathrm{d}x}{(N_t-1)!}$$

$$\hat{D}_n = \frac{\int_0^{\infty} \log^2(1+\hat{p}_n^{\star}(A)\lambda_n x) x^{N_t-1} e^{-x}\, \mathrm{d}x}{(N_t-1)!} - \hat{E}_n^2.$$

Based on C.L.T, Gaussian Approximation,

$$\sum_{n=1}^{N}\sum_{k=1}^{K} \xi_{nk} \log\left(1+\lambda_n \hat{p}_n^{\star}(A)\|\mathbf{h}_{nk}\|^2\right) \sim N\left(\sum_{n=1}^{N} K\rho_n \hat{E}_n, \sum_{n=1}^{N} K\left[\rho_n \hat{D}_n + \rho_n(1-\rho_n)\hat{E}_n^2\right] \right)$$

Simulations

Antennas	4	User mobility	Random Direction
$P_{\max}$ of the BS	46dBm	User speed v	$3\ km/h$
The cell radius	250m	File size B	0.5 Gbs
The path loss model	$30.6+37.6\log_{10}(d/m)$	No. of time slots N	360
SNR	10dB	Time slot duration Δ_t	10s
Subcarriers K	1200	Availability ρ_n	U[0 1]
Subcarrier spacing Δ_f	15kHz	Outage ε	0.05

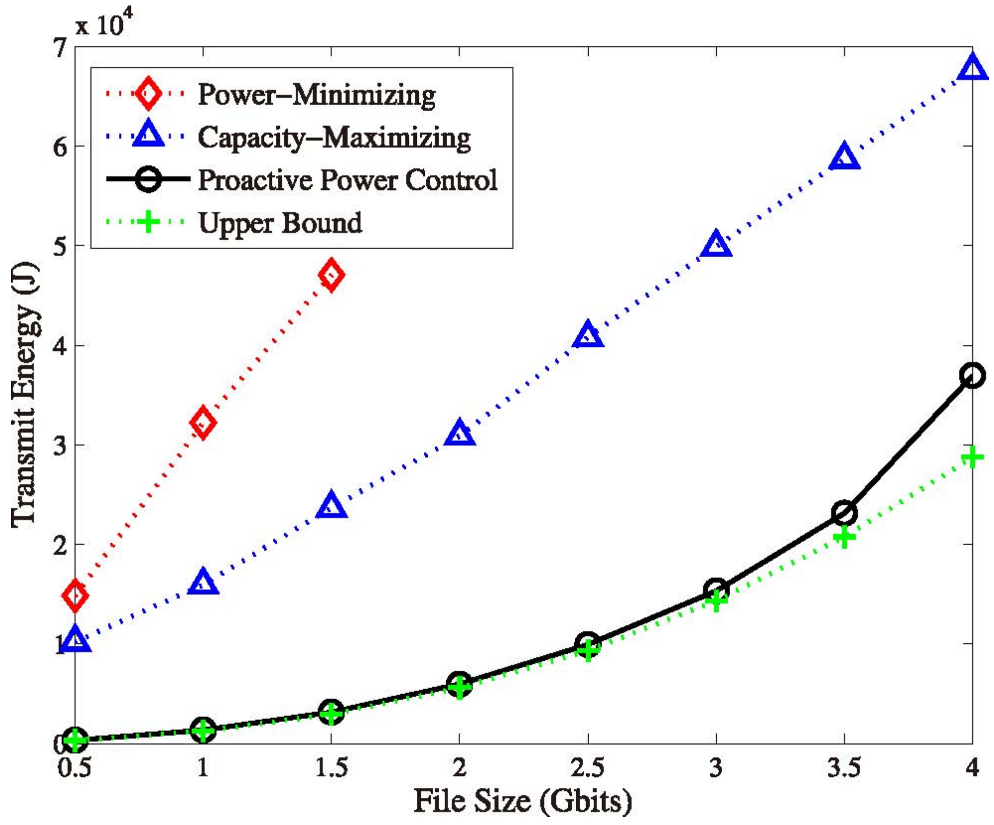
Performance Benchmarks:

1.Power-Minimizing: minimize power per time slot;

2.Capacity-Maximizing: maximize capacity per time slot;

3.Upper-Bound:perfect rate prediction based proactive power allocation.

Simulations



Average total transmit energy consumption of the proposed method and three relevant policies

1.The proposed policy ≈ upper bound especially for small to medium B

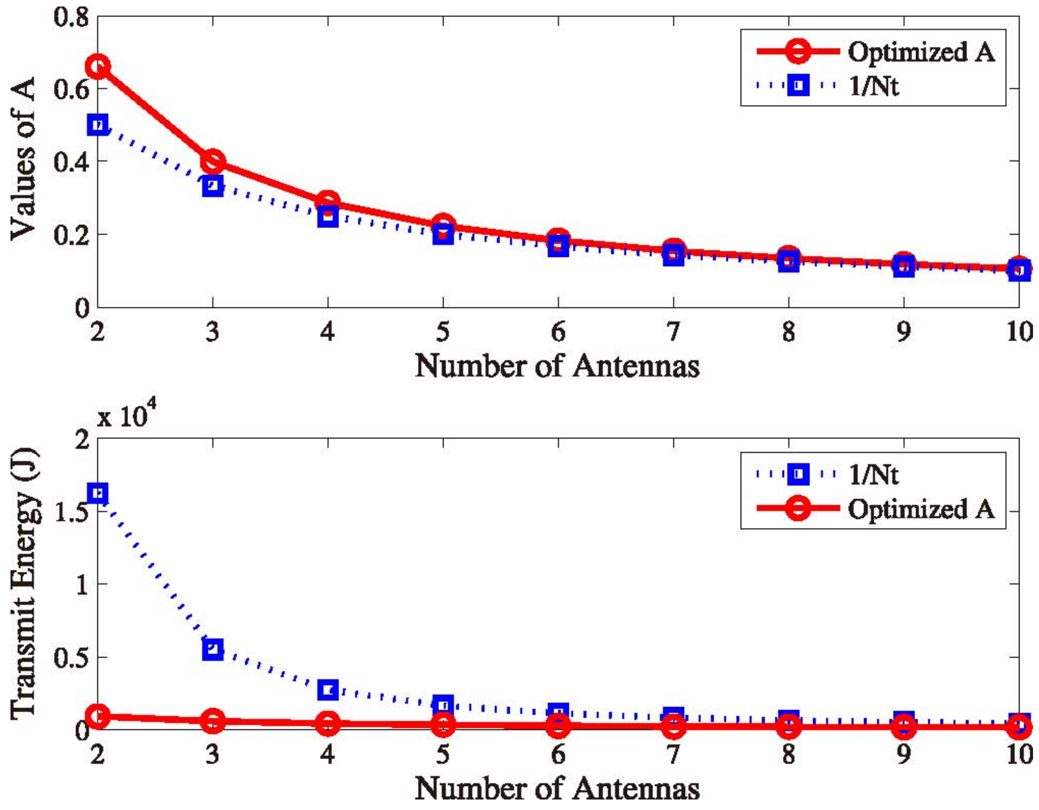
⇓

statistical information provide most gain of proactive resource allocation!!!

2.The proposed policy exhibits evident performance gain to the benchmarks.

Power-Minimizing policy supports small size file under the outage constraint

Simulations



Comparison of the optimal values of A and $\frac{1}{N_t}$ for different number of antennas

1. For large N_t , $A = \frac{1}{N_t}$

$$\left\| \boldsymbol{h}_{nk} \right\|^2 \rightarrow N_t, \ N_t \rightarrow \infty$$

2. For small N_t ,
Energy gain $A \gg$ energy gain $\frac{1}{N_t}$

Conclusions

- Context-aware proactive power allocation policy with average channel gains and statistical information of available frequency resources of the network

- A new approximation for the outage-based QoS constraint

- A hierarchical algorithm to solve the average total transmit energy minimization problem

Thank you for your attention!