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Disclaimer: The main focus of this report is on the main results of the research within 2015-2016 and are based on the extensions to the submitted and under preparation journal papers. The status of the report is CONFIDENTIAL.

Abstract: Reliable and accurate localization of users is critical for many applications in wireless networks. In range-based localization, the position of a node (agent) can be estimated using the distance measurements to nodes with known positions (anchors). Optimal subcarrier power allocation of the anchors reduces positioning error and improves network lifetime and throughput. The Cramer-Rao bound for a network localization problem using orthogonal frequency division multiplexing signals, for both unicast and multicast transmissions is obtained. The bound is formulated considering uncertainties in the wireless channel as well as the agents' positions, and it is the base of a power allocation problem. The results show that power allocation for multicast reduces the total power compared to unicast designs. Moreover, our robust design outperforms non-robust counterparts.

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Introduction

High-accuracy localization is of critical importance in many location-based applications and services, e.g., cellular positioning, search and rescue tasks, blue-force tracking, communication, and military systems [1,2]. Wireless network localization (WNL) refers to the process of finding the positions of users (agents) using range measurements to nodes with known positions (anchors). The transmission power of the nodes plays an important role in WNL, not only in terms of lifetime and throughput, but also in positioning accuracy [3]. Therefore, an optimal power allocation is important for reducing power consumption and increasing positioning accuracy. Several power allocation methods have been presented for single-carrier transmission in synchronized networks [4,5]. These methods include the positioning accuracy as either an objective or a constraint, using fundamental performance limits. In [6,7], the fundamental limits of wideband localization have been derived in terms of squared position error bound (SPEB) and directional position error bound (DPEB) for the case of single-carrier signals. To overcome the uncertainties on the network parameters, a robust power allocation has been proposed in [8] by converting the optimization problem to semidefinite programming (SDP) and second-order cone programming (SOCP) forms by minimizing SPEB and maximum DPEB (mDPEB) subject to a total power constraint. In [4,5,8], it is assumed that when an anchor sends a signal to a particular agent other agents cannot listen (unicast assumption). However, for a synchronous network, this leads to suboptimal solutions in terms of total required power for the anchors. Moreover, unlike in [4-8], current and emerging communications standards generally employ multi-carrier signals, in particular orthogonal frequency division multiplexing (OFDM). Multicarrier transmissions are beneficial when the data rates increase and wider bandwidths are needed. Also, they are less susceptible to interference compared to single carrier transmission as interference may only affect a small number of subcarriers. In this report, I have presented a framework for robust power allocation in an OFDM WNL with uncertainties on the network parameters, which include the channel coefficients and the positions of the agents. Specifically, I have used the SPEB as the fundamental limit of the localization accuracy. Our main contributions are summarized as follows.

- I have obtained the SPEB for OFDM signals in a synchronous network, for the cases of (i) deterministic unknown agent positions and channels; (ii) a collections of agent positions and channels drawn from suitable distributions.
- I have developed a method to obtain subcarrier power allocations that minimizes the total transmitted power subject to a constraint on the average or maximum SPEB, for both unicast and multicast transmissions.

System Model

Consider a wireless network with N_b anchors with known positions and N_a agents with unknown positions. The sets of agents and anchors are denoted by $\mathcal{N}_a=\{1,...,N_a\}$ and $\mathcal{N}_b=\{N_a+1,...,N_a+N_b\}$. The two-dimensional positions of k-th agent and j-th anchor are denoted by $\mathbf{q}_k=[x_k,y_k]^T$ for k belong to $\mathcal{N}_a$ and $\mathbf{q}_j=[x_j,y_j]^T$ for j belong to $\mathcal{N}_b$. Anchors may be elements of the fixed infrastructure like cellular base stations, whereas agents may be mobile users. We assume all nodes are perfectly synchronized and use OFDM transmissions from anchors to agents to localize the agents. We consider either multicast and unicast communication.

Multicast operation

Each anchor j sends an OFMD signal, which is received by all agents. We denote as $\mathbf{r}_{k,j}$ the Nx1 vector representing the received signal by agent k due to the transmission of anchor j, after cyclic prefix removal and transformation to the frequency domain. The vector $\mathbf{r}_{k,j}$ can be expressed as [9]

$$\mathbf{r}_{k,j} = \boldsymbol{\Gamma}(t_{k,j})\mathbf{B}_j\mathbf{F}_{L_{k,j}}\mathbf{h}_{k,j} + \mathbf{w}_{k,j},$$

in which $\mathsf{B}_j = \mathrm{diag}\{B_j[n]\}_{n=0}^{N-1}$ is an NxN diagonal matrix representing the signals transmitted by anchor j on the subcarriers, $\mathsf{F}_{L_{k,j}}$ represents the first $L_{k,j}$ columns of the NxN discrete Fourier transform (DFT) matrix with $L_{k,j}$ being the number of channel taps between nodes j and k, $\mathsf{h}_{k,j} = [h_{k,j}^{(1)}, , h_{k,j}^{(L_{k,j})}]^{\mathsf{T}}$,

$$\Gamma(t_{k,j}) = \mathrm{diag}\{\exp(-j2\pi n t_{k,j}/T)\}_{n=0}^{N-1}$$

where $t_{k,j}$ is the arrival time of the first path and is given by $t_{k,j} = \|\mathbf{q}_k - \mathbf{q}_j\|/c$ with c representing the speed of light, T is the OFDM symbol duration, and $\mathbf{w}_{k,j}$ is an Nx1 noise vector distributed as $\mathcal{CN}(0,\sigma_w^2\mathbf{I}_N)$. We introduce **r** as the vector representation of all the received waveforms, given by $\mathbf{r}=[\mathbf{r}_1^T \cdots \mathbf{r}_{N_a}^T]^T$ with $\mathbf{r}_k = [\mathbf{r}_{k,N_a+1}^T \cdots \mathbf{r}_{k,N_a+N_b}^T]^T$.

Unicast operation

Each anchor j will send different OFDM signal to each agent. In terms of the model, the only difference is that we replace $\mathbf{B}_j$ by $\mathbf{B}_{k,j}$.

Goal

Our goal is to minimize the total transmission power (related to $\mathrm{P}_j = \mathbf{B}_j^H\mathbf{B}_j$ for multicast and to $\mathrm{P}_{k,j} = \mathbf{B}_{k,j}^H\mathbf{B}_{k,j}$ for unicast) to obtain a certain positioning accuracy in the presence of uncertainties in the channel and the agent positions.

Squared Position Error Bound

Squared position error bound (SPEB) is a measure of performance in terms of localizatio accuracy obtained using the Fisher information matrix (FIM) of the parameters. In this section we briefly explain the SPEB that is used later on for the robust power allocation problem.

We obtain the FIM for the parameter of interest

$$\boldsymbol{\eta} = [\mathbf{q}_1^{\mathsf{T}}, \ldots, \mathbf{q}_{N_a}^{\mathsf{T}}, \boldsymbol{\theta}_1^{\mathsf{T}}, \ldots, \boldsymbol{\theta}_{N_a}^{\mathsf{T}}]^{\mathsf{T}},$$

where $\mathbf{q}_k$ denotes the location of the agents and $\boldsymbol{\theta}_k$ includes the real and imaginary parts of the channel coefficients from the agents to the anchors. We are interested to obtain the equivalent FIM (EFIM) of the parameters related to the location of the agenets. The EFIM of the agents' positions can be obtained as

$$\mathbf{J}_e(\mathbf{q}) = \frac{2}{c^2\sigma_w^2} \sum_{j \in \mathcal{N}_b} \mathrm{diag}\{\lambda_{1,j}\mathbf{J}_r(\phi_{1,j}), \ldots, \lambda_{N_a,j}\mathbf{J}_r(\phi_{N_a,j})\}$$

where the ranging direction matrix (RDM)

$$\mathbf{J}_r(\phi_{k,j}) = \mathbf{u}_r(\phi_{k,j})\mathbf{u}_r^{\mathsf{T}}(\phi_{k,j})$$

with

$$\mathbf{u}_r(\phi_{k,j}) = [\cos\phi_{k,j} \;\; \sin\phi_{k,j}]^{\mathsf{T}}$$

in which

$$\phi_{k,j} = \pm \arctan(y_k - y_j)/(x_k - x_j)$$

represents the angle between the j-th anchor and k-th agent with positive sign for $x_k > x_j$ and $y_k > y_j$ or $x_k < x_j$ and $y_k < y_j$ and negative sign otherwise. The ranging information intensity (RII) $\lambda_{k,j}$ can be decomposed as information for the channel $\mathbf{h}_{k,j}$ and a reduction due to the uncertainty of the channel $\mathbf{h}_{k,j}$:

$$\lambda_{k,j} = \mathbf{h}_{k,j}^{\mathsf{H}}\mathbf{M}_{k,j}^{(1)}\mathbf{h}_{k,j} - \mathbf{h}_{k,j}^{\mathsf{H}}\mathbf{M}_{k,j}^{(2)}\mathbf{h}_{k,j}$$

where

$$\mathrm{M}_{k,j}^{(1)} = \mathbf{F}_{L_{k,j}}^{\mathrm{H}} \mathbf{D}^{\mathrm{H}} \mathbf{P}_j \mathbf{D} \mathbf{F}_{L_{k,j}}$$

in which

$$\mathrm{D}=\mathrm{diag}\{\mathrm{j}2\pi n/T\}_{n=0}^{N-1}$$

and

$$\mathrm{M}_{k,j}^{(2)} = \boldsymbol{\Xi}_{k,j}^{\mathrm{H}} \boldsymbol{\Sigma}_{k,j}^{-1} \boldsymbol{\Xi}_{k,j}$$

in which

$$\Xi_{k,j} = \mathbf{F}_{L_{k,j}}^{\mathrm{H}} \mathbf{P}_j \mathbf{D} \mathbf{F}_{L_{k,j}}$$

and

$$\Sigma_{k,j} = \mathbf{F}_{L_{k,j}}^{\mathrm{H}} \mathbf{P}_j \mathbf{F}_{L_{k,j}}$$

Using the fact that the EFIM of agent positions is of block-diagonal form, we define the SPEB for k-th agent as

$$\mathrm{P}_k(\{\mathbf{p}_j\}) \triangleq \mathrm{tr}\{\mathbf{J}_e^{-1}(\mathbf{q}_k)\},$$

where $\mathbf{p}_j$ is an Nx1 vector taken from the main diagonal of $\mathbf{P}_j$, and

$$\mathrm{J}_e(\mathbf{q}_k) = \frac{2}{c^2\sigma_w^2} \sum_{j\in\mathcal{N}_b} \lambda_{k,j} \mathbf{J}_r(\phi_{k,j}).$$

It can be observed that SPEB for the agents is a function of input power $\mathbf{P}_j$, the relative angle between the agents and anchors $\phi_{k,j}$, and channel coefficients $\mathbf{h}_{k,j}$. The SPEB cannot be used directly as a constraint for power allocation, since it presumes knowledge of the agents positions, which are precisely the parameters to be estimated. In contrast, having no knowledge at all regarding the positions of the agents would mean that we cannot perform any intelligent power allocation. In this section, we consider a middle ground where we average over a set of channels and agents' positions. This information can be in the form of a set or, more generally, a distribution. Including this side information will allow us to perform a robust power allocation.

The expected SPEB is defined as

$$\overline{\mathcal{P}}_k(\{\mathbf{p}_j\}) \triangleq \mathrm{tr}\{\mathbb{E}_{\boldsymbol{\eta}}[\mathbf{J}_e^{-1}(\mathbf{q}_k)]\},$$

where the expectation is carried out over the distribution of the channel coefficients $\mathbf{h}_{k,j}$ and agents' positions $\mathbf{q}_k$. To evaluate expected SPEB we consider a scenario in which the agents are supposed to be located at some positions, with certain channel coefficients and relative angles defined as $\mathrm{h}_{k,j}^{(-)}$ and $\phi_{k,j}^{(-)}$, respectively. Then, the set of possible channel coefficients and relative angles are generated as

$$\mathrm{h}_{k,j}^{(+)} = \mathbf{h}_{k,j}^{(-)} + \boldsymbol{\Delta}\mathbf{h}_{k,j}$$

and

$$\phi_{k,j}^{(+)} = \phi_{k,j}^{(-)} + \Delta\phi_{k,j}$$

with $\Delta h_{k,j}$ being randomly chosen from a zero-mean complex Gaussian distribution with covariance matrix $\boldsymbol{\Sigma}_{\mathbf{h}_{k,j}}^{(+)}$, and $\Delta\phi_{k,j}$ being randomly chosen from a uniform distribution in the interval $[-\Delta_{k,j}, \Delta_{k,j}]$ where $\Delta_{k,j}$ is the maximum uncertainty of relative angle between j-th anchor and k-th agent.

We approximate the SPEB averaged over random parameters using numerical averaging over M_q realizations

$$\overline{\mathcal{P}}_{k,\mathrm{ap}}(\{\mathbf{p}_j\}) = \frac{1}{M_q}\sum_{m=1}^{M_q} \mathrm{tr}\{[\mathbf{J}_{e,k,m}^{-1}(\{\mathbf{p}_j\})]\},$$

in which

$$\mathrm{J}_{e,k,m}(\{\mathbf{p}_j\}) = \frac{2}{c^2\sigma_w^2}\sum_{j\in\mathcal{N}_b} \lambda_{k,j,m}^{(+)}\mathbf{J}_r(\phi_{k,j,m}^{(+)}),$$

where

$$\lambda_{k,j,m}^{(+)} = (\mathbf{h}_{k,j,m}^{(+)})^{\mathrm{H}}(\mathbf{M}_{k,j}^{(1)} - \mathbf{M}_{k,j}^{(2)})\mathbf{h}_{k,j,m}^{(+)},$$

with $\mathrm{h}_{k,j,m}^{(+)}$ and $\phi_{k,j,m}^{(+)}$ being

$$\mathrm{h}_{k,j,m}^{(+)} = \mathbf{h}_{k,j}^{(-)} + \boldsymbol{\Delta}\mathbf{h}_{k,j,m}$$

$$\phi_{k,j,m}^{(+)} = \phi_{k,j}^{(-)} + \Delta\phi_{k,j,m},$$

Similarly, one can define the robust SPEB for the worst case uncertainty on the channel coefficient and agents' positions. Here, we do not get into the details of the proof for the case of robust SPEB and only present the result in the simulation in comparison with the ergodic design. Using the above definitions, we propose the ergodic and robust power allocations for OFDM wireless network localization in the next section.

Ergodic and Robust Power Allocation

We can now formulate an optimization problem to minimize the total power required to achieve a certain positioning accuracy on the agents' positions, considering the uncertainty on the channel coefficients and relative angles between anchors and agents.

Ergodic Power Allocation

The ergodic power allocation can be written as

$$\begin{aligned} \underset{\{\mathbf{p}_j\}}{\text{minimize}} \quad & \sum_{j\in\mathcal{N}_b} \mathbf{1}^{\mathsf{T}}\mathbf{p}_j \\ \text{subject to} \quad & \bar{\mathcal{P}}_k(\{\mathbf{p}_j\}) \leq \beta,\ \forall k \in \mathcal{N}_a \\ & \mathbf{p}_j \succeq \mathbf{0},\ \forall j \in \mathcal{N}_b, \end{aligned}$$

Where the total power from the anchors to the agents is minimized subject to constraints on the positioning accuracy of each agent and non-negative power vector. The localization constraint here is based on the numerical averaging over different channel coefficients and agents' positions. It is assumed that each anchor is broadcasting the signal to different agents (multicast). For the case of unicast the power allocation can be reformulated by replacing the sub-script j by k,j and minimizing the total power as the sum of the power vectors from all sets of the power vector for each anchor and agent as

$$\textstyle\sum_{k\in\mathcal{N}_a}\sum_{j\in\mathcal{N}_b}\mathbf{1}^{\mathsf{T}}\mathbf{p}_{k,j}$$

Robust Power Allocation

Robust power allocation can be written as

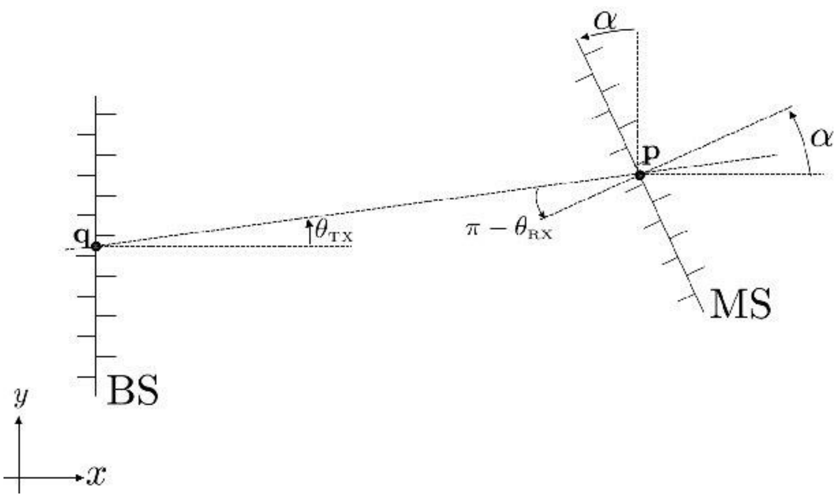
$$\begin{aligned} & \underset{\{\mathbf{p}_j\}}{\text{minimize}} && \sum_{j \in \mathcal{N}_b} \mathbf{1}^{\mathsf{T}} \mathbf{p}_j \\ & \text{subject to} && \mathcal{P}_k^{max}(\{\mathbf{p}_j\}) \leq \beta, \ \forall k \in \mathcal{N}_a \\ & && \mathbf{p}_j \succeq \mathbf{0}, \ \forall j \in \mathcal{N}_b, \end{aligned}$$

where the total power from different anchors is minimized subject to the certain positioning accuracy for the worst case SPEB (maximum SPEB) for a given uncertainty on the channel coefficients and agents' positions and non-negative power vectors. Again, the problem can be reformulated for the case of unicast transmission by replacing the sub-script j by k,j.

The ergodic form of the power allocation can be solved using Semidefinite programming, while the robust form can be solved iteratively for a given initial value for the power vector that eventually converges to the robust solutions. Here, the goal is not to get into the details of mathematically proposing the solutions for the ergodic and robust power allocations. Instead, I have presented the results in the simulation results.

5G Localization

Here, we summarize a 5G localization approach for the line-of-sight (LOS) scenario for position and orientation estimation.

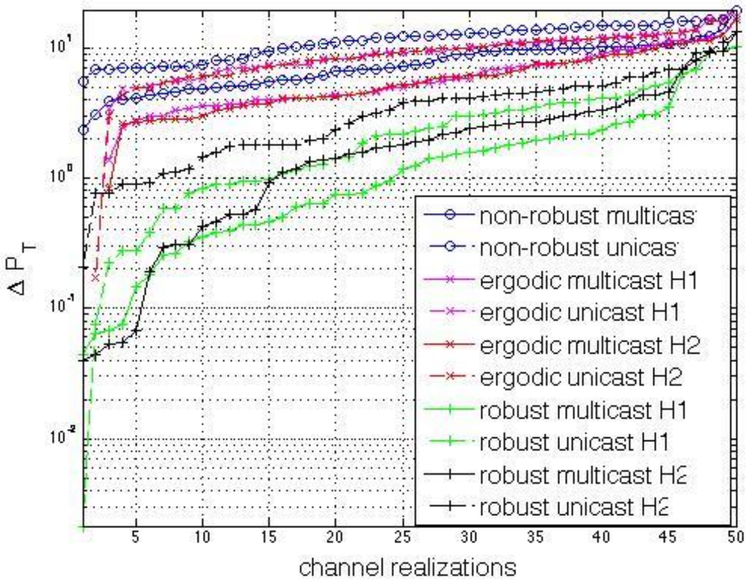


Millimeter-wave (mm-wave) and massive MIMO, which are both candidate features for 5G communication networks, are also enabling technologies for accurate positioning and device orientation estimation. The limited scattering and high-directivity are unique characteristics of mm-wave channel and massive MIMO, respectively. In the LOS conditions, angle-of-departure (AOD) θ_{Tx} is used for the estimation of position **p** while angle-of-arrival (AOA) θ_{Rx} provides the estimation of orientation α. By exploiting these features together with beamforming, we provide sufficient conditions under which the Fisher information matrix (FIM) of the AOA, AOD and time-of-arrival (TOA) of the LOS path of a scenario illustrated in Fig. 1 is non-singular, in the presence of an unknown channel. A non-singular FIM is a necessary condition for the identifiability of the position and orientation of the user.

Main Results

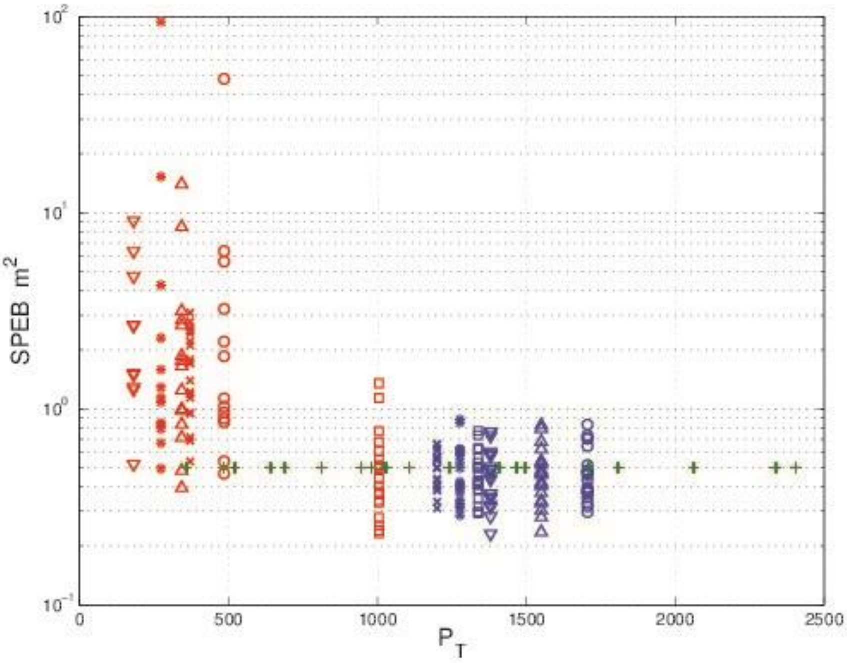
Ergodic and Robust Power Allocations

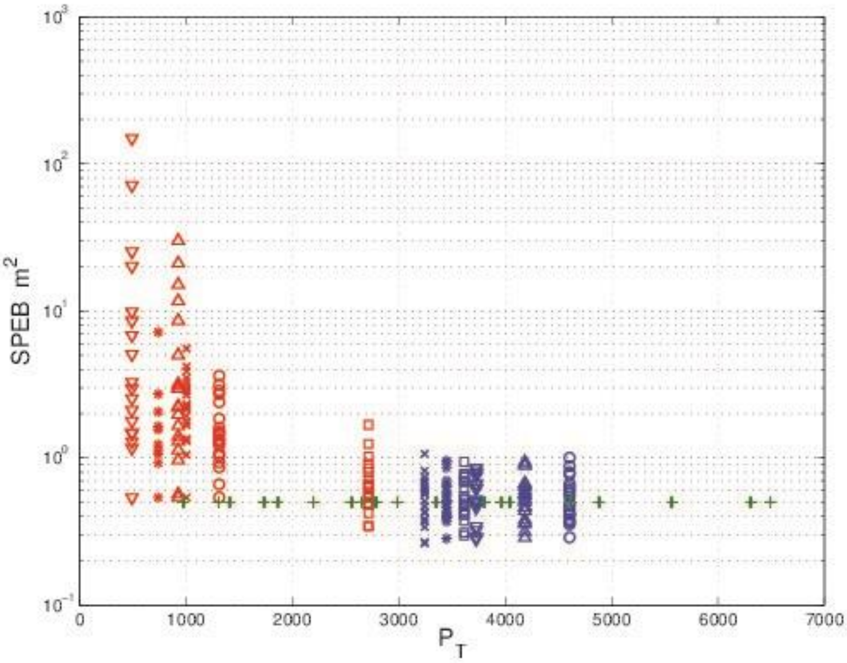
Here, we briefly propose the main result regarding the ergodic and robust power allocations in comparison with their single carrier counterparts for a given bandwidth.



It can be observed that both ergodic and robust power allocations for multicarrier signals save total power considerably compared to their single carrier counterparts for a given bandwidth for both multicast and unicats transmissions. In the above figure H1 and H2 stands for different types of uncertainties on the channel coefficients. Specifically, H1 stands for the norm based uncertainty by considering the channel as a vector and H2 stands for the scalar uncertainty by considering the channel as a set of coefficients and applying the uncertainty constraint to each channel tap. The relative power increase is around 8 for non-robust for single carrier compared to the multicarrier, while it is of the order of 6 for ergodic and 2.5 for the robust designs.

Ergodic Power allocation





The above figures show the required total power for all the anchors to satisfy the SPEB constraint for multicast and unicast methods based on ergodic (blue) and non-ergodic designs (red) for several channel coefficients before the movement.

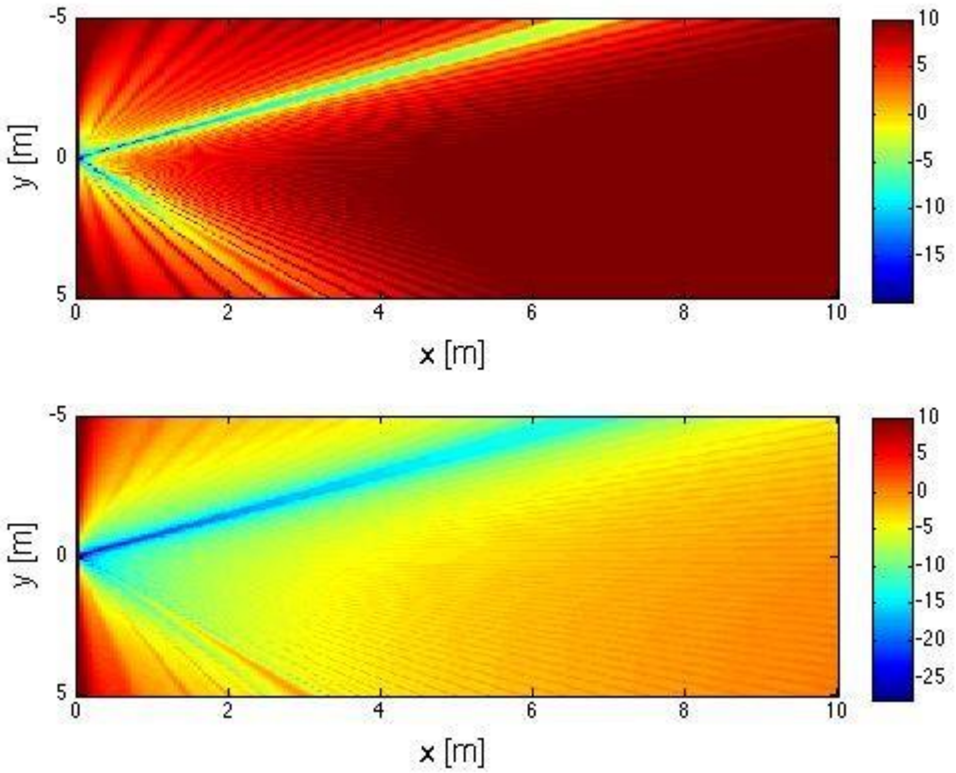
We observe that the unicast method requires more power than multicast, as

unicast requires more transmissions, i.e., unicast requires four more transmissions. However, the unicast distribution does not need four times the power of the multicast distribution. This is the core of doing per-subcarrier allocation instead of simply power allocation for fixed signals. The ergodic allocation tends to require more power than the non-robust allocation, for both unicast and multicast that is one of the reasons to obtain closer value to the desired 0.5 m^2 SPEB on the average. The increase in total power based on the robust allocation is different depending on the channel coefficients before the

movement. For some channels the increase is much more than the others to reduce the SPEB to the values closer to the desired value on the average, and for other cases (e.g., the one with square marker) ergodic design does not require much more total power. Finally, the allocation using actual multicast and actual unicast in most of the realizations requires less total power to achieve the desired value of SPEB. This is due to complete knowledge of the channel after movement.

5G Localization

Next, we present the result for the 5G position and orientation estimation in LOS conditions.



From the above simulations we observe that for the BS located at (0,0) and the MS moving in different locations in a 10mx10m square the lowest possible error both in terms of position and orientation estimation is in the direction of the beams. Moreover, the error can be further reduced by sending sufficiently close beams (the beams at the top) in a particular direction as it is clear from the above result.

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List of Publications

[1] Arash Shahmansoori, Gonzalo Seco-Granados, Henk Wymeersch, " 5G Position and Orientation Estimation through Millimeter Wave MIMO", IEEE Global Telecomm. Conf. (GLOBECOM) 2015.

[2] Arash Shahmansoori, Gonzalo Seco-Granados, Henk Wymeersch, " Robust Power Allocation for OFDM Wireless Network Localization", IEEE International Conference on Communications (ICC) 2015.

[3] A. Shahmansoori, R. Montalban, J. A. Lopez-Salcedo, G. Seco-Granados, " Design of OFDM Sequences for Joint Communications and Positioning Based on the Asymptotic Expected CRB," in International Conference on Localization and GNSS (ICL-GNSS). 2014.

[4] A. Shahmansoori, R. Montalban, G. Seco-Granados, "Optimal OFDM Pilot Sequences for Time-Delay and Channel Estimation Based on the Expected CRB for a Large Number of Subcarriers," in The 15th IEEE International Workshop on Signal Processing Advances in Wireless Communications (SPAWC). 2014 .

[5] A. Shahmansoori, R. Montalban, G. Seco-Granados, "Effect of Channel Variability on Pilot Design for Joint Communications and Positioning in OFDM ," in International Smposium on Wireless Communications (ISWCS). 2014.

[6] Arash Shahmansoori, Gonzalo Seco-Granados, and Henk Wymeersch, "Robust and Ergodic Power Allocation for OFDM Wireless Network Localization, Submitted to IEEE Transactions on Wireless Communications, May 2016.

Secondment

I completed my secondments at Chalmers university of technology from (December, 2014-July, 2015 and April, 2016-July, 2016) and completed the required period of 10.8 months.

Training Event

Multi-Pos kick-off workshop, Sept. 2013, TUT. Multi-pos autumn workshop, Dec 2013, HW/Prague. Multi-pos autumn workshop Barcelona, Nov. 2014, UAB. Multi-pos spring school Toulouse, April. 2015, ENAC.