Application

2015-03-31

2015-04389	Tufvesson, Fredrik	NT-14

Information about applicant

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Information about application

Call name: Forskningsbidrag Stora utlysningen 2015 (Naturvetenskap och teknikvetenskap)

Type of grant: Projektbidrag

Focus: Fri

Subject area:

Project title (english): Highly accurate phase based positioning

Project start: 2016-01-01

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Review panel applied for: NT-14, NT-13

Classification code: 20203. Kommunikationssystem, 20205. Signalbehandling

Keywords: Radiobaserad positionering, flervägsutbredning, parameterföljning, fledimensionell estimering, mätningar

Funds applied for

Year:	2016	2017	2018	2019
Amount:	1,204,727	1,088,299	1,191,757	1,150,130

Descriptive data

Project info

Project title (Swedish)*

Fasbaserad positionering med hög noggrannhet

Project title (English)*

Highly accurate phase based positioning

Abstract (English)*

Radio based positioning is an area that have received a lot of interest lately due to the introduction of Bluetooth Low Energy and Apple's iBeacon. While this technology relies on received signal strength from a number of nodes for positioning, the accuracy in the range estimates and hence also the position estimates is quite poor. Another alternative for radio based positioning is to use the ultra wideband (UWB) signaling. For ubiquitous navigation and tracking solutions we, however, would like to avoid the requirement of using special equipment or any special radio signal. In this application we propose to investigate a novel phase based approach to radio based positioning and tracking. Such an approach would enable high resolution tracking of movements, with an accuracy in the order of fractions of a wavelength, i.e. centimeter level precision at standard cellular and wireless frequencies around 2 or 5 GHz.
The project is divided into three work packages: 1) parameter tracking methods for multipath aided positioning, 2) channel characterization and modeling for radio based positioning, and 3) phase based multipath aided tracking and positioning methods. We will thus study both the theoretical foundations for phase based positioning and tracing, perform measurement to characterize and model the channel behavior from a positioning perspective and analyze the performance of the base based positioning and tracking approach.

Popular scientific description (Swedish)*

Positioneringslösningar baserat på radiosignaler blir idag mer och mer populära. Apple har nyligen lanserat sin lösning iBeacon, vilken har väckt stor uppmärksamhet p g a dess potential att ge lokal positionsinformation i t ex affärer, museer, hotell etc. Dessvärre har denna teknik sina brister eftersom positionsestimatet bygger på mottagen signalstyrka och därmed ofta är behäftad med stora fel. Ett annat alternativ för att erhålla bättre positionsinformation är att använda en speciell typ av signaler, s k ultrabredbandssignaler. Dessa kan ge hög noggrannhet, men de kräver i sin tur speciella sändare och mottagare. I detta projekt strävar vi istället efter att utveckla och analysera en ny metod för radiobaserad positionering och navigering. Metoden bygger på att man estimerar och följer fasen på den signal som sänds ut från t ex vanliga mobiltelefoner. Genom att arbeta med fasen för att ta fram positionsestimaten går det att dramatiskt förbättra kvaliteten på dem. I projektet strävar vi efter en noggrannhet på ett par centimeter på positioneringen, detta kan jämföras med traditionella mobilbaserade positioneringsalternativ där felen ofta ligger i storleksordingen av hundra meter eller ett tiotal meter.
För att ta fram en lösning som fungerar i praktiken kommer vi att i projektet arbeta med både teori och begränsningar för fasbaserad positionering, mätning och modellering av radiokanalens egenskaper såväl som prestandautvärdering och jämförelser med andra tekniker.

Project period

Number of project years*

4

Calculated project time*

2016-01-01 - 2019-12-31

Classifications

Select a minimum of one and a maximum of three SCB-codes in order of priority.

Select the SCB-code in three levels and then click the lower plus-button to save your selection.

SCB-codes*

2. Teknik > 202. Elektroteknik och elektronik > 20203. Kommunikationssystem

2. Teknik > 202. Elektroteknik och elektronik > 20205. Signalbehandling

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Enter a minimum of three, and up to five, short keywords that describe your project.

Keyword 1*

Radiobaserad positionering

Keyword 2*

flervägsutbredning

Keyword 3*

parameterföljning

Keyword 4

fledimensionell estimering

Keyword 5

mätningar

Ethical considerations

Specify any ethical issues that the project (or equivalent) raises, and describe how they will be addressed in your research. Also indicate the specific considerations that might be relevant to your application.

Reporting of ethical considerations*

Projektet är av teknisk natur och vi har gjort bedömningen att det inte finns några betydelsefulla etiska överväganden att ta hänsyn till för projektet.

The project includes handling of personal data

No

The project includes animal experiments

No

Account of experiments on humans

No

Research plan

Radio based positioning assisted by multipath propagation

Purpose and aims

In this application we propose to investigate a phase based approach to radio based positioning. It is well known that the phase of a received continuous wave changes by 360 degrees for a movement of one wavelength relative to the receiver (e.g., a base station or access point). Given that: 1) it is possible to separate different multipath components, 2) estimate and track the phase variations of the individual multipath components, and 3) that those phase variations can be detected from various angles relative to the moving node, it is possible to perform high resolution phase based positioning and tracking of the movement (e.g., of a transmitting cell phone). Here, by high resolution we mean accuracy in the order of fractions of a wavelength, i.e., centimeter level precision at standard cellular and wireless frequencies around 2 or 5 GHz.

To perform the desired phase estimation from different angles, we can take advantage of the multipath channel. Traditionally, the multipath channel has been seen as an obstacle for positioning and navigation solutions, but by using the fact that there usually are a number of distinct scatterers surrounding a mobile station, at least in indoor, urban or sub-urban scenarios, we can achieve the goal of picking up the phase variations from various angles with respect to the mobile station. Since all the multipath signals stem from a single source, we have a coherent system at hand, which is important for this kind of high resolution approach. By using a large number of antennas at the receiver side it is possible to separate the contributions stemming from individual scatterers and track the phase evolution of the multipath components. The dominating scatterers are often fixed but located at random or unknown positions. It is thus hard to relate a detected phase change to a particular movement of the transmitter. To overcome this problem when we estimating a particular movement, we aim to apply methods from the area of image processing, where the so-called structures from motion problems often appear, to estimate the movement.

Although we are convinced that the above methodology works, and we have performed a first proof-of-principle in one test scenario [1], there are several important open research questions to be answered. We group those into three areas:

1) To separate and track the multipath components from each other we have to rely on multiple antennas at the base station when the bandwidth is decreased. With UWB signals it is relatively straightforward to separate and track the evolution of different multipath components due to the high temporal resolution. This tracking is though tricky for more moderate bandwidths using only single, or a few, antennas. We can, however, trade bandwidth versus antennas and hence maintain the possibility to separate the multipath components from each other by using many antennas at the base station side, as for example done in massive MIMO. Such a set of base station antennas offers a new level of angular and spatial resolution, and makes it possible to separate and track the individual multipath components. This improved resolution is actually one of the reasons why the system offers good communication performance and is able to separate also closely spaced users, but it can also be used to take radio based positioning to a new level. Important topics for our purpose include the fundamental problem of the tradeoff between antennas and bandwidth, how to perform robust estimation and tracking of the phase of individual multipath components, and how to assess and use some kind of quality information of the estimates.
2) As in any other wireless system the properties of the wireless channel ultimately determine the possible performance of the tracking and navigations schemes, and there were many “ifs” and

"buts" regarding the radio channel in the problem description above. Hence an understanding of the properties of the radio channel with respect to positioning problems is essential for the development, analysis and performance evaluation of the new positioning approach. There is currently a lack of channel models suitable for analysis of radio based positioning, and there is a lack of understanding of many fundamental properties of the radio channel being highly relevant for positioning. Among questions of interest are: How does the power from so-called diffuse multipath components scale with the bandwidth and evolve while a user is moving? For how long movement can a normal scatterer typically be seen (i.e., the visibility region of a single scatterer)? How do the phase changes from normal objects in our environment, not just point scatterers or plane surfaces, evolve during movements? In the project we will therefore perform channel measurements, analyze properties relevant for positioning and develop channel models that, at different levels of complexity, are suitable for analysis and performance assessment of radio based positioning methods, with special emphasis on phase based positioning techniques.

3) In this project we will analyze and derive high resolution methods for phase based multipath aided positioning and tracking, but what are the performance limitations? How can we analyze the positioning and tracking performance? What are the best estimation methods for the envisioned phase based positioning approach when the scatterers are at unknown positions? What are the conditions from a channel perspective for the approach to work? We have performed preliminary measurements, and have indications that it is possible to trade bandwidth against antennas at the base station side in order to realize positioning with centimeter accuracy also in unknown environments using bandwidths that are utilized in the wireless systems of today (20-40 MHz in LTE/LTE-A). This should be compared to conventional time delay based methods which give a resolution of around 10 m (as determined by the speed of light divided by the bandwidth for non-coherent systems). From an algorithm perspective more rigorous analysis is, however, necessary to establish the validity of the approach. Thus, in the project we will work on a theoretical framework for analysis of phased based positioning and tracking, and we will investigate suitable positioning algorithms when the scatterers are located at unknown positions. We will also study the performance limitations of the phase based positioning approach

Survey of the field

For positioning and tracking the use of ultra wideband (UWB) and time of arrival (TOA) or time difference of arrival (TDOA) measurements have been studied extensively. The work on positioning in this application will be based on ideas from TOA based positioning, but we will use phase information from the radio signal instead of TOA estimates. The high angular resolution offered by a large number of antennas at the base station enables this novel way for radio based positioning. Usually, in UWB systems the position estimates are based on delay estimates of the first arriving component from several sources, and some kind of trilateration is performed to get the position estimates. An overview of different positioning and localization methods can be found in [1]. Due to the existence of multipath transmission, the fundamental limits of ranging and localization using wideband signals are studied extensively in [1] [4]. One should, however, note that there is a difference in the phase based tracking approaches compared to the time delay approaches. The phase based approach that we aim for can be seen as a variant of a *coherent* MIMO radar, where the static scatterers act as coherent receiving nodes given that we can separate them by multiple antennas at the base station.

The performance of coherent MIMO radars is analyzed in [27] where also the gains compared to non-coherent systems are highlighted.

There are, however, also other UWB approaches where delays of multipath components are used [5] to estimate the position of a transmitter or a receiver. In [6] a positioning method is presented based on a single source delay measurements and floorplan information. By using the concept of virtual sources, whose locations were known through the floorplan, a single antenna receiver was positioned and tracked. The performance bounds of this technique in terms of the Cramer Rao Lower Bound were then further analyzed in [21]. In [25] and [26] early work on ranging using multipath components was performed. It was concluded that multipath components, in their case a single ground reflection, could offer large performance gains for the range estimates. However, without precise knowledge of the propagation conditions (the depth of the reflection point in their considered case) the performance gains were lost. With more multipath components one can overcome this limitation and perform localization in unknown environments, as demonstrated in [7]. There we have extended the multipath aided positioning concept to the case of UWB without using floorplan information. The directions to the virtual sources, the scatterers, are instead estimated based on so called structure from motion techniques from node localization in sensor networks. For those networks, there is usually an initialization process where positions of the nodes are estimated. The initialization problem based on TOA measurements in sensor networks has been studied in [7], where solutions to the minimal case of three transmitters and three receivers in the plane is given, but no practical solver for the minimal case in 3 dimensions (3D) is provided. Initialization based on TDOA and TOA measurements is studied in [9], where solutions were given to non-minimal cases, e.g. ten receivers and five transmitters in 3D. A line of previous works impose additional assumptions on the measurements. By assuming that a pair of receiver and transmitter has the same location, a closed form solution is proposed in [10] for TOA based positioning in 3D. In [11] and refined in [12], far field approximation (assuming that the distances from the transmitters to receivers are considerably larger than the distances between receivers) was utilized to solve both the TOA and TDOA problems.

For the phase based multipath assisted positioning it is necessary to be able to separate the multipath components (MPCs) and track the corresponding parameters for delay, angle of arrival, and complex amplitude. There are several maximum likelihood based (or approximations thereof) extraction methods available, among the most widely used are SAGE [14], Extended Kalman Filter (EKF) [15] and RIMAX [16], but only EKF offers an inherent capability to actually track the multipath components in a phase coherent way from snapshot to snapshot. In [24] an approach named KEST – Kalman Enhanced Super Resolution Tracking was proposed where the channel parameters first were estimated using SAGE and then the parameters were tracked using a Kalman filter. This approach has the advantage that the linearization problem when using EKF for parameter estimation becomes less prominent [24], and it has been applied successfully for parameter tracking both in simulations and in practical experiments. The tracked delays have also been used for positioning with promising results [23] without known positions of the scatterers using simultaneous localization and mapping (SLAM) implemented through a particle filter. As this approach is based on time delays the mean position error is in the order of 10 m using 100 MHz of bandwidth for the transmission, but it is another indication of the advantages using the multipath components for positioning with or without prior knowledge of the floorplan information.

Based on an EKF implementation and the framework for the UWB based structure from motion estimation framework we have, as mentioned in the introduction, been able to perform a first proof-of-principle of phase based positioning [1] where we track the phases of the MPCs using the EKF and translate the phase changes to distance changes and use this as input to the structure from motion positioning and scatterer estimator [7]. For a circular movement and a 2D propagation assumption we have managed to reach a standard deviation for the position error of 4 cm using a bandwidth of 40 MHz. For more complex movement patterns and propagation scenarios we have, however, also encountered some problems with the projection of the phase changes. We are, however, confident that the issue with 2D movements in 3D propagation environments can be overcome with proper adjustments of the structure from motion estimation framework.

Channel modelling for multipath aided positioning

From the channel measurements we need to characterize the channel and derive a suitable channel model that can be used for design and evaluation of both systems and algorithms. There are essentially four different approaches to channel modeling [17]:

- Measured impulse responses,
- Deterministic models,
- Stochastic (analytical) models, and
- Geometry based stochastic channel models.

The geometry based stochastic channel models (GSCM) combine the idea of geometrical descriptions from ray tracing methods, though in a very simplified manner, with a stochastic part describing, e.g., the variations of the environment. The GSCMs have generally reasonable complexity and offer some advantages compared to the other models [18]:

- They have correspondence to the physical reality
- They inherently model temporal evolution of the channel as the transmitter (Tx), Receiver (Rx) or the scatterers move.
- Dependencies between channel parameters usually "come for free" with the geometrical description

Due to those reasons we are convinced that a GSCM can provide the necessary framework for a channel model suitable for radio based positioning. Compared to current state-of-the-art GSCMs, like the IMT-advanced model [20] and COST 2100 model [19], we need however to extend those models and include more realistic behavior of how the multipath components appear and disappear, how the phase evolves during movements from objects that neither acts as point sources, nor as perfectly plane reflecting surfaces. To some degree this has been investigated in the radar literature [22], but not for this particular purpose. Another important task is, of course also, to find appropriate descriptions for how the bandwidth affects the behavior of those properties. To complement the measurements ray tracing approaches will also be used, but the problem is here that most available ray tracers rely on ideal descriptions of the scattering behavior.

Project description

The project will be performed by a PhD student supervised by the main applicant Fredrik Tufvesson.

The project is divided into three work packages corresponding to the purpose and aims as given in the introduction:

- WP1, parameter tracking methods for multipath aided positioning

- WP2, channel characterization and modeling for radio based positioning
- WP3, phase based multipath aided tracking and positioning methods

See Figure 1 for an overview of the relation between the work packages and a rough timeline.

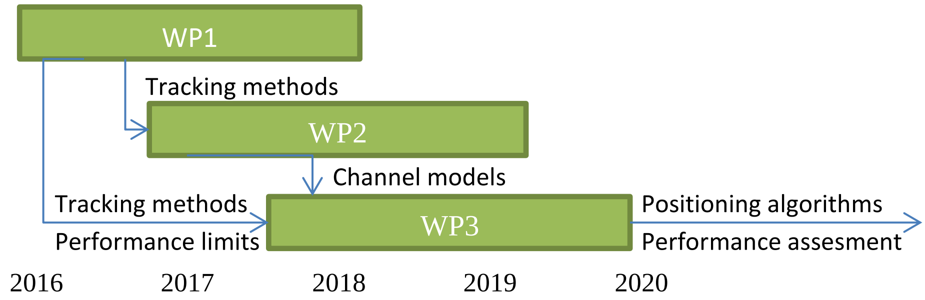

Figure 1. Interrelation between the work packages and rough timeline.

WP1: Parameter tracking for multipath aided positioning

An understanding of reliable parameter estimation and tracking methods of the multipath components (MPCs) is the foundation for the further work. In this WP we will analyze the differences in requirements for parameter estimation methods for channel analysis (as they are conventionally used for) and for positioning. For positioning it is desirable to track long sequences of contributions from the MPCs and to estimate many multipath components at the same time in order to span all dimensions of the physical movement. For this it is often necessary to also track somewhat weaker components as they can come from other directions than the main components. We will work on adjustments of available high resolution parameter estimation algorithms; initially the focus will be on EKF. It has the ability to accurately track the phase of the multipath components. The algorithm distinguishes and makes a joint estimation of the specular components that we use for the positioning and of the diffuse multipath that acts more like interference from a positioning point of view. One drawback with the EKF in its current form is that it is derived primarily for parameter estimation of the multipath components, and it is quite conservative when it comes to the detection of specular components. For positioning it is preferred to be able to track many MPCs over long time, and hence some parameter adjustments might be necessary to get the desired functionality. Otherwise the EKF provides a nice framework as it, besides the level of diffuse multipath, also reports the quality of the parameter estimates (in terms of the covariance matrix), power of the estimated diffuse multipath, death birth processes, which then in turn can be used to assess the quality of the resulting position estimate [21]. While our initial investigations indicate that we get better phase tracking with EKF directly compared to the case of first using an ML-based estimator such as SAGE followed by tracking using a Kalman filter, we aim to make a systematic comparison between the two approaches. This WP will provide the theoretical foundation, but also practical algorithms, for tracking of multipath components, with special emphasis on tracking for phase based multipath aided positioning.

WP2: Channel characterization and modeling for multipath aided positioning

Channel measurements are necessary to analyze the true behavior of the parameter tracking methods, but we also need measurements to characterize the behavior of the channel from the positioning perspective. In this WP we will through measurements investigate the behavior of MPSs more in detail. Typically in current measurement efforts there is a focus on the behavior of clusters rather than on individual MPCs, but for positioning we are more interested in the behavior of the latter. Especially we will investigate the visibility regions of single MPCs and the corresponding shadowing regions, i.e. regions where an MPC is not visible for a shorter time. We will further investigate the deterministic phase behavior from normal objects in our environment and the behavior of diffuse multipath from a positioning perspective. Diffuse multipath tends to follow the clusters and the deterministic MPCs; currently, however, there is a lack of understanding of the dynamic behavior of the diffuse multipath and how to model it between successive snapshots. Another channel related question we aim to investigate is how those effects and parameters scale with bandwidth. Do we need a high bandwidth to suppress the power of the diffuse multipath?

Channel models suitable for radio based positioning will be developed based on the measurements. Our first assumption is to use a cluster based model for channel descriptions. We aim to extend the current COST 2100 model with a proper description of realistic behavior of individual MPCs, probably by defining suitable death birth processes for the dominant MPCs and adjusting the phase behavior according to the characteristics extracted from the measurements. We will also work on a more proper description of the diffuse multipath taking the variations of the of the channel behavior due to the bandwidth used into account.

This WP will give us further insights on the channel behavior necessary to take the next steps in radio based positioning and result in more accurate channel models suitable for multipath aided positioning. These results will, together with the tracking results from WP1 be the basis for the work in WP3.

WP3: Phase based multipath aided tracking and positioning methods

As described in the introduction we plan to further push the limits of what is possible in terms of radio based positioning by using the tracked phase information from the multipath components instead of delay estimates for extracting the position estimation.

As a starting point we will use our framework developed for UWB based tracking using the multipath components and study the conditions from a channel perspective for the phase based approach to work? Based on the coherent MIMO radar approach in [27] we will develop a theoretical framework for analysis of phased based positioning and tracking, and study the performance limitations. So far we have mostly focused on the tracking of position movements, but we also need to study methods for achieving the initial position estimates. There a combination of the phase estimates and the delay estimates could give a set of candidates for the initial starting point, which in turn can be further analyzed. We will also analyze how to include the extracted quality measures from WP1 to improve the position estimate. Theoretical studies on the Cramer Rao Lower Bound for UWB based multipath assisted navigation and tracking have shown a significant improvement in the position estimates when including information about the diffuse multipath and we will thus investigate how to include such information also for the phase based multipath assisted approach.

This WP will use the results from WP1 and WP2 and result in optimized algorithms for multipath aided phase based positioning achieving centimeter level accuracy using radio signals with moderate bandwidths in the order of 20-40 MHz. We will also provide quality measures for the position estimates and environment dependent performance bounds for the positioning.

Significance

Radio based positioning has received a lot of interest lately and is an enabler for many applications. The methods used generally today have however limited accuracy and therefore also limitations in their use. In this project we will study a new approach for radio based positioning, an approach that, to the best of our knowledge has not been studied before, which based on the received phase from multipath components of the radio channel. We will analyze and develop methods for radio based positioning and tracking with accuracy that have never been seen before for the bandwidths used in cellular systems of today. Compared to conventional time delay based methods (TOA/TDOA with triangulation between base stations) we aim for a 100-1000 fold improvement to get tracking accuracies down to a centimeter scale. Using conventional cellular radio signals only, this is in our opinion this is the most promising radio based approach for positioning enabling centimeter level accuracy. Such accuracy will obviously open up for a whole new range of applications, in the cellular network itself, but also in areas like medicine, automation, manufacturing and transportation.

Preliminary results

Our results on positioning and tracking in unknown environments using UWB measurements are presented in [7]. There we have shown that it is possible to position a single transmit antenna using only a single receive antenna by tracking delay changes of the multipath components in an unknown indoor environment with centimeter level accuracy. In those early experiments we moved the Tx antenna within a cube of 30x30x30 cm and we were able to reconstruct the movement with an RMS error of 1.3 cm using a novel combination of structure from motion algorithms from image processing, and delay estimation and tracking algorithms from the channel analysis area. Based on those encouraging results we have then started to investigate phase tracking methods and we have seen that it is possible to resolve and track the phase of the individual multipath components at a level detailed enough to perform phase based positioning with a precision that have not been seen before for the common bandwidths of 20-50 MHz as used in cellular systems of today. Our first results in the area have been accepted for presentation in IEEE ICC 2015 Workshop on Advances in Network Localization and Navigation [1]. In Figure 1 we show an example of phase tracking from a synthetic case using a bandwidth of 50 MHz at a frequency of 2.6 GHz and a real indoor case measured with a bandwidth of 40 MHz. In the synthetic case there are four scatterers randomly located in 3D (coordinates in meters) around the terminal, which moves in a circle with the radius of 1 m.

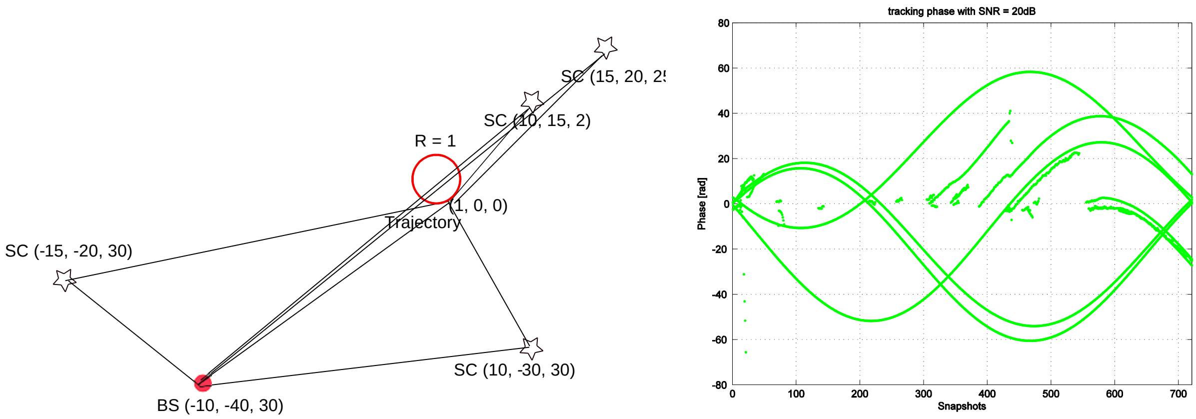

Figure 1 (left) Setup of a synthetic case for initial investigations. Four scatterers are placed at various distances from the terminal in the middle, and the base station receives the sum of the four contributions, the line-of-sight plus noise. (right) The phase of the tracked multipath components in the synthetic case estimated with the EKF algorithm.

The base station has a stacked circular array (4 circles with 16 antennas in each circle) with 64 dual polarized antenna elements. For this synthetic case we use measured antenna responses and the received signal at each antenna element is the sum of the line-of-sight components, the four scattered components and noise, the SNR is 20 dB. In the right of Figure 1 we show the phase of the estimated and tracked multipath components using a standard EKF implementation for parameter estimation. As seen we are able to track the phase evolution almost ideally, also for very small movements. The tracked estimated phases correspond well to the physical reality, showing the potential for the phase based tracking. We should mention that in this synthetic case we could as well have performed straightforward beamforming to come to the same phase responses, but in a more cluttered case (as in reality) we have to use high resolution parameter estimation methods, such as EKF, to separate the contributions of the individual multipath components. In Figure 2 we show phase tracking results from the measurements for a circular and square movement, in this case for the four strongest multipath components, together with the estimated positions. The results presented here provide a first proof of principle that positioning using signals with moderate bandwidths with accuracy down to centimeter level is possible and hence can be a promising candidate for future positioning systems using already existing infrastructure.

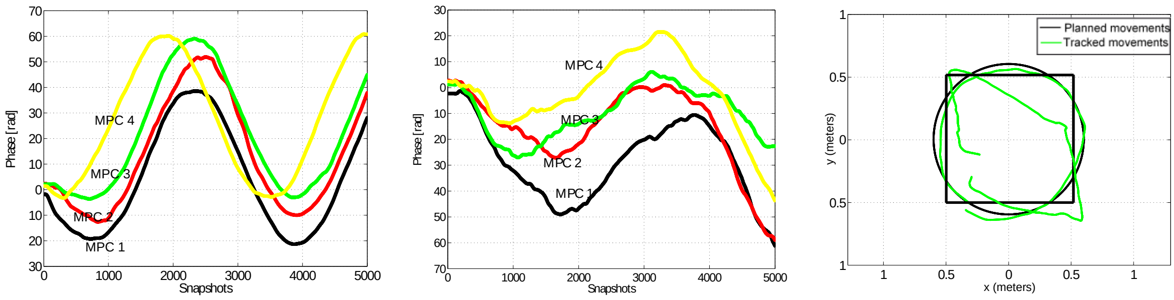

Figure 2. (left) The phase of a tracked multipath component in an indoor measured case when the transmitter is moved in a similar circle as in the synthetic case. As seen, the phase evolution reveals a sinusoidal distance variation to the scattering point. (mid) Tracked phases for a square movement. (right) Estimated positions and planned movement, as seen the circular shape is well estimated, but there is a projection issue for the square movement [1].

Equipment

The Department of Electrical and Information Technology has the most advanced experimental equipment for MIMO channel measurements, putting it in a unique position to successfully conduct the research program of this project.

The cornerstone of the laboratory equipment is the RUSK LUND channel sounder. It is a fast switched broadband MIMO channel sounder covering frequencies 5.1-5.8 GHz, 2.2-2.7 GHz and 235-387 MHz. The sounder can perform dynamic measurements with an arbitrary number of base station antennas (<8000) with a maximum bandwidth of 240 MHz.

At the department we also have a virtual array setup based on a vector network analyzer and antenna positioners that is really useful for detailed and specific studies in static environments, especially when it comes to evaluating different array geometries and initial channel investigations.

The group has developed a library of high-resolution algorithms for the evaluation of the measurement data (ESPRIT, SAGE, RIMAX, and others). This valuable output from our previous experiments will greatly accelerate the evaluations of the propagation measurements.

The department further offers a fully equipped research radio laboratory with all facilities necessary to design advanced equipment including integrated analog, digital and high frequency circuits. Any necessary calibrations of the measurement equipment, the sounder and measurement antennas can be done in the anechoic chamber of the department, which allows measurements in the frequency ranges of interest for this application.

We have an established cooperation with the center for mathematics, the department of automatic control at Lund University and MAPCI – the Mobile and Pervasive Computing Institute at Lund

University. Together we are about to establish Lund Positioning Laboratory, where we besides the competence from those partners also will have access to a furnished apartment positioning lab and a advanced camera based positioning system for verification measurements.

Finally, at the department we also have a real time massive MIMO test bed, the first of its kind in the world and to our best knowledge the only publically announced operational real-time massive MIMO test bed. The test bed can be used to perform real time implementations of large array systems of up to 100 antenna elements, and will be used as a tool for doing truly parallel channel measurements for phase based positioning.

International and national collaboration

In the area of radio based positioning the main collaboration is with Centre for Mathematical Sciences (Prof. K. Åström) and Dept. of Automatic Control (Prof. B. Benhardsson) at Lund University.

Another main partner in Sweden is Linköping University and the group led by Prof. E.G. Larsson. Currently we are collaborating on massive MIMO within our joint strategic research area ELLIIT (www.liu.se/elliit). Together with Linköping University we are also participating in an EU-project in the area of massive MIMO. Other members are Ericsson AB, IMEC in Belgium, KU Leuven in Belgium, Infineon in Austria and Telefonica in Spain.

In the area of channel modeling for MIMO and UWB we have in the past worked a lot with Aalto University in Finland (P. Vainikainen before, now K. Haneda) and also UCL (Université catholique de Louvain) in Belgium (C. Oestges). This cooperation has been performed within the Scandinavian NORDITE project WILATI and within the European COST 2100 and COST IC 1004 projects. Together we have developed a multi-link MIMO and polarization modeling framework that now is adopted in the COST 2100 model. The joint channel modeling efforts continue in the COST IC 1004 project.

The research group has a strong network with other universities and research institutes, with well-established collaboration in terms of joint projects, publications or applications:

- Within Sweden: joint projects with other universities (Chalmers, Högskolan i Halmstad, and Linköping University) and industry (Ericsson, Sony Mobile, Volvo Cars, Volvo Trucks, FOI).
- Worldwide partners with joint publications: University of Southern California, US (A. Molisch), TU Vienna, Austria, (C. Mecklenbräuker), FTW Forschungszentrum Telekommunikation Wien/Austrian Institute of Technology, Austria (T. Zemen), Alcatel-Lucent Bell labs, USA (T. Marzetta), Aalto University, Finland (K. Haneda), UCL Belgium (C. Oestges)

Other grants

In 2011 Tufvesson got a major grant from SSF on distributed antenna systems. This five year project involves five other seniors (which were also co-applicants), two post docs and four PhD students. As a project leader, Fredrik is expected to spend 20% of his working time on this project. Tufvesson is also co-applicant on a VR application on massive MIMO systems with Prof. Ove Edfors, "Wireless channel models with high spatial resolution". There is no overlap between the two projects, the other project deals with channel modelling for massive MIMO communication.

Tufvesson spends around 60% of his time on research and will spend 20% of his time on this project.

References

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Interdisciplinarity

My application is interdisciplinary

☐

An interdisciplinary research project is defined in this call for proposals as a project that can not be completed without knowledge, methods, terminology, data and researchers from more than one of the Swedish Research Councils subject areas; Medicine and health, Natural and engineering sciences, Humanities and social sciences and Educational sciences. If your research project is interdisciplinary according to this definition, you indicate and explain this here.

Click here for more information

Scientific report

Scientific report/Account for scientific activities of previous project

Budget and research resources

Project staff

Describe the staff that will be working in the project and the salary that is applied for in the project budget. Enter the full amount, not in thousands SEK.

Participating researchers that accept an invitation to participate in the application will be displayed automatically under Dedicated time for this project. Note that it will take a few minutes before the information is updated, and that it might be necessary for the project leader to close and reopen the form.

Dedicated time for this project

	Role in the project	Name	Percent of full time
1	Applicant	Fredrik Tufvesson	20
2	Participating researcher	Doktorand	85

Salaries including social fees

	Role in the project	Name	Percent of salary	2016	2017	2018	2019	Total
1	Applicant	Fredrik Tufvesson	10	230,335	237,245	244,362	251,693	963,635
2	Participating researcher	Doktorand	85	444,821	458,165	471,910	486,067	1,860,963
	Total			675,156	695,410	716,272	737,760	2,824,598

Other costs

Describe the other project costs for which you apply from the Swedish Research Council. Enter the full amount, not in thousands SEK.

Premises

	Type of premises	2016	2017	2018	2019	Total
1	Kontor och lab	100,751	91,015	99,667	96,186	387,619
	Total	100,751	91,015	99,667	96,186	387,619

Running Costs

	Running Cost	Description	2016	2017	2018	2019	Total
1	labmaterial, dator	mätaccessoarer, dator	100,000		50,000		150,000
2	Resor	till konferenser, mätningar	50,000	50,000	50,000	50,000	200,000
	Total		150,000	50,000	100,000	50,000	350,000

Depreciation costs

Depreciation cost	Description	2016	2017	2018	2019

Total project cost

Below you can see a summary of the costs in your budget, which are the costs that you apply for from the Swedish Research Council. Indirect costs are entered separately into the table.

Under Other costs you can enter which costs, aside from the ones you apply for from the Swedish Research Council, that the project includes. Add the full amounts, not in thousands of SEK.

The subtotal plus indirect costs are the total per year that you apply for.

Total budget

Specified costs	2016	2017	2018	2019	Total, applied	Other costs	Total cost
Salaries including social fees	675,156	695,410	716,272	737,760	2,824,598		2,824,598
Running costs	150,000	50,000	100,000	50,000	350,000		350,000
Depreciation costs					0		0
Premises	100,751	91,015	99,667	96,186	387,619		387,619
Subtotal	925,907	836,425	915,939	883,946	3,562,217	0	3,562,217
Indirect costs	278,820	251,874	275,818	266,184	1,072,696		1,072,696
Total project cost	1,204,727	1,088,299	1,191,757	1,150,130	4,634,913	0	4,634,913

Explanation of the proposed budget

Briefly justify each proposed cost in the stated budget.

Explanation of the proposed budget*

Huvuddelen av budgeten går till en doktorand, vilken kommer att arbeta 85% i projektet.
Projektledare, tillika huvudsökande, förväntas arbeta 10% direkt i projektet.

För projektets utförande kommer vi gjöra mätnignar, vi tar inte upp några avskrivningskostnader för utrustning, men däremot behövs mätaccessoarer i form av antenner, kablar, hårddiskar etc. Större delen ligger under första året, men baserat på resultat förväntas uppföljande mätningar under år 3.

Resor täcker framförallt deltagande i konferenser, men även mindre lokala resor i samband med mätningar.

Lokaler och OH följer institutionens riktlinjer för full kostnadstäckning.

Other funding

Describe your other project funding for the project period (applied for or granted) aside from that which you apply for from the Swedish Research Council. Write the whole sum, not thousands of SEK.

Other funding for this project

Funder	Applicant/project leader	Type of grant	Reg no or equiv.	2016	2017	2018	2019

CV and publications

CV

CV for Fredrik Tufvesson

1. Higher education qualification(s)

Master of Science M.Sc. in Electrical Engineering from Lund University, Lund, Sweden. Thesis title: On Harmonic Penetration in Urban Low- and Medium-Voltage Networks (in Swedish). June 1994
Licentiate in Engineering in Applied Electronics from Lund University, Lund, Sweden. Thesis title: Channel Related Optimization of Wireless Communication Systems. February 1998

2. Doctoral degree

PhD in Applied electronics / Radio systems, Department of Applied Electronics, Lund University. Thesis title: Design of Wireless Communication Systems - Issues on Synchronization, Channel Estimation and Multi-Carrier Systems. September 2000. Advisor: Prof. Torleiv Maseng

3. Postdoctoral positions

System specialist, Fiberless society/Branoc Networks, September 2000 – January 2002.

4. Qualification required for appointments as a docent

Docent in Radio systems August 2007.

5. Current position

Professor of Radio Systems, May 2014 – present, Dept. of Electrical and Information Technology, Lund University. Approximately 60 % time for research.

6. Previous positions and periods of appointment

- Associate Professor of Radio systems, Dept. of Electrical and Information Technology, Lund University, June 2003-May 2014
- CTO/founder, Hepkie/ResQU AB, startup developing equipment for location of disaster victims and missing people. 2009-2014
- Researcher at the Department of Electroscience, Lund University. February 2002 - June 2003
- Co-founder and system specialist, Branoc Networks, Lund, Sweden. September 2001 - January 2002
- System specialist, Fiberless Society, Lund, Sweden. October 2000 - August 2001
- Ph.D. candidate at the Department Applied Electronics, Lund University. January 1995 -September 2000

7. Interruption in research

Parental leave June-September 2002, June-September 2004, May-September 2008.

8. Supervision

As main advisor for the following students finishing with a PhD:

- Carl Gustafson, "60 GHz Wireless Propagation Channels: Characterization, Modeling and Evaluation", Dec. 2014;
- Meifang Zhu, "Geometry-based Radio Channel Characterization and Modeling: Parameterization, Implementation and Validation", Sept. 2014;
- Taimoor Abbas, "Measurement Based Channel Characterization and Modeling for Vehicle-to-Vehicle Communications, February 2014.
- Rohit Chandra "Antennas, Wave Propagation, and Localization in Wireless Body Area Networks" March 2014. Anders J Johansson was active (co-)advisor
- Palmi Thorbergsson, "Signal Modeling and Data Reduction for Wireless Brain Machine Interfaces" in Nov. 2012, Anders J Johansson was active (co-)advisor
- Fredrik Harrysson, "Multiple Antenna Terminals in Realistic Environments - A Composite Channel Modeling Approach", May 2012.

As co-advisor for students that defended PhD thesis, where I took an active role as advisor: Anders Bernland (May 2012), Andres Alayon Glazunov (March 2009), Shurjeel Wyne (March 2009), Johan Kåredal (Feb. 2009), Peter Almers (May 2007). For the last four I took a major role as advisor

Main advisor for the following Ph.D. students: Jose Flordelis, expected PhD in 2015; Muhammad Atif Yaqoob expected PhD in 2016; Mikael Nilsson, expected PhD in 2016; Dimitrios Vlastaras, expected PhD in 2017; Joao Vieira, expected PhD in 2017; Xuhong Li, expected PhD in 2019.

Post-doctoral supervision: Peter Almers, June 2007-Sept 2008. Multi-link channel characterization; Shurjeel Wyne, April 2009-April 2010, mm wave systems; Johan Kåredal, March 2009-August 2011, Vehicular communication; Ghassan Dahman, Aug 2011-present, Distributed antenna systems

9. Other information of relevance to the application

Awards: Co-author of 4 papers that were granted best paper/student paper awards. Awards in Ventrue Cup 2006, 2011, 2013. Stipend to realize and commercialize a cell phone based search and rescue system, which was the foundation for our startup ResQU AB.

Management experience: Deputy head of the department of electrical- and information technology (Jan 2015-present) board member (2007-2014); deputy head of the Lund part of the strategic research area ELLIIT, board member (2012-present); PI of a larger SSF project on distributed antenna systems (26 MSEK/5 years, 2012-2016); Director for SSF High Speed Wireless Center (2011-2012), board member (2009-2010); National Swedish delegate in COST 2100 and IC 1004; CTO and founder Hepkie AB (2009-2012).

Publications: 7 book chapters, 54 journal papers, 115 conference papers, 4 patent applications. H-index 34 (Google scholar March. 2015). See www.eit.lth.se/staff/fredrik.tufvesson for a full list of publications.

Editorship and review assignments: Associate editor for IEEE Transactions on Wireless Communications, 2009 -- 2013. Reviewer for a number of journals such as IEEE Trans. Comm., IEEE Trans. Wireless Comm., IEEE Trans. Vehicular Techn., IEEE Sel. Areas in Comm., IEEE Trans. Ant. and Prop., IEEE Trans. Sig. Proc.

Conference chairing and technical program committee memberships: Co-chair of Wireless Communication Symposium at IEEE International Conference on Communications 2013. In total we managed 462 submitted papers and 260 Technical Program Committee members. 175 papers were presented at the conference held in Budapest, Hungary, June 2013. Co-chair of Dependable Vehicular Communications (DVC), ICC workshop 2015, London, U.K., June 2015. Member of the organizing committee and financial officer for SWE-CTW, Swedish Communication Technologies Workshop, 2012.

Technical Program Committee member for IEEE Vehicular Technology Conference (2013, 2011, 2010, 2005), IEEE ICC Workshop on Advances in Network Localization and Navigation (2015, 2014, 2013), IEEE International Conference on Communication (2014, 2013, 2010), IEEE IEEE Globecom (2013, 2014, 2007), IEEE International Conference on Ultra-Wideband, ICUWB (2009, 2006), International Conference on Localization and GNSS (2015)

International collaboration: Strong network with other universities and research institutes, with well-established collaboration in terms of joint projects, publications or applications, examples include: University of Southern California, US (A. Molisch), TU Vienna, Austria, (C. Mecklenbräuker), FTW Forschungszentrum Telekommunikation Wien/Austrian Institute of Technology, Austria (T. Zemen), Alcatel-Lucent Bell labs, USA (T. Marzetta), Aalto University, Finland (K. Haneda), UCL Belgium (C. Oestges). More than 50% of the papers are written jointly with international collaborators.

Selected invited talks and tutorials:
Tutorial at ICC 2015, ``Massive MIMO for 5G: From Theory to Practice'', London, U.K., June 2015.
Invited talk at International Solid State Circuit Conference, ISSCC 2015, "More Bits via the Same Spectrum - Massive MIMO Opportunities", San Francisco, USA, Feb. 2015
Tutorial at ICC 2013, ``Massive MIMO systems'', Budapest, Hungary, June 2013.
Tutorial at ICASSP 2012, ``Very Large MIMO'', Kyoto, Japan, March 2012.
Globecom Industry Forum 2011, ``Know thy channel -– considerations for reliable and scalable ITS technologies'', Houston, USA, Nov. 2011.
``60 GHz impulse radio for short range wireless communication –- something for the future?'', Vienna University of Technology, Oct. 2010.

Major research grants and project experience:
2013-2016 “Wireless Communication in Automotive Environment'', FFI/ Vinnova, 71 MSEK, co-applicant
2012-2016 “Distributed Antenna Systems for Highly Efficient Wireless systems'', Swedish Foundation for Strategic Research (SSF), 27 200 kSEK, PI
2011-2014 “mmWave-pulses above 10 Gbps'', VR multi project grant, 9 600 kSEK, co-applicant
2011-2014 “Scaling up MIMO: Challenges and Opportunities with Very Large Arrays'', VR multi project grant, 12 800 kSEK, co-applicant
2011-2013 “Chanel modelling for multi user MIMO with multiple base stations'', VR, 2 400 kSEK, main applicant
2008-2010 “Channel modelling for cooperative and interfering MIMO systems'', VR project grant, 2 250 kSEK, main applicant
2007-2010 ”WILATI+'', NORDITE/Vinnova, 4 638 kSEK, project leader
2004 “MIMO channel sounder'', KAW, 4 400 kSEK equipment grant, co-applicant
Participant and WP leader in EU projects MAMMOET, MAGNET, MANGET beyond

Publication list

Publication list for Fredrik Tufvesson 2015-2008

An updated publication list, and many full text papers, can found at http://www.eit.lth.se/staff/fredrik.tufvesson

For conference papers, citation data is given for papers with more than 10 citations

1. Journal articles & letters

1. T. Abbas, J. Nuckelt, T. Kürner, T. Zemen, F. Tufvesson: Simulation and Measurement Based Vehicle-to-Vehicle Channel Characterization: Accuracy and Constraint Analysis, IEEE Transactions on Antennas and Propagation 2015 (in press)
2. G. Dahman, F. Rusek, M. Zhu, F. Tufvesson: Massive MIMO performance evaluation based on measured propagation data, IEEE Wireless Communications Letters 2015 (in press)
3. X. Gao, O. Edfors, F. Rusek, F. Tufvesson: Massive MIMO performance evaluation based on measured propagation data, IEEE Transactions on Wireless Communications 2015 (in press). Number of citations: 14
4. R. Chandra, A. Johansson, M. Gustafsson, F. Tufvesson: A Microwave Imaging based Technique to Localize an In-body RF-source for Biomedical Applications, IEEE Transactions in Biomedical Engineering, 2014. (In press)
5. D. Vlastaras, T. Abbas, D. Leston, F. Tufvesson: Vehicle Detection through Wireless Vehicular Communication EURASIP Journal on Wireless Communications and Networking, pp. 146-, 2014.
6. R. He, A. Molisch, F. Tufvesson, Z. Zhong, B. Ai, T. Zhang: Vehicle-to-Vehicle Propagation Models With Large Vehicle Obstructions Intelligent Transportation Systems, IEEE Transactions on, Vol. 15, No. 5, pp. 2237-2248, 2014. Number of citations:5
7. L. Bernado, T. Zemen, F. Tufvesson, A. Molisch, C. F. Mecklenbrauker: Time- and Frequency-Varying K -Factor of Non-Stationary Vehicular Channels for Safety-Relevant Scenarios, Intelligent Transportation Systems, IEEE Transactions on, No. 99, 2014. Number of citations:2
8. A. Molisch, F. Tufvesson: Propagation channel models for next-generation wireless communications systems, IEICE Transactions on Communications, Vol. E97B, No. 10, pp. 2022-2034, 2014. Number of citations:3
9. C. Gustafson, K. Haneda, S. Wyne, F. Tufvesson: On mm-Wave Multi-path Clustering and Channel Modeling, IEEE Transactions on Antennas and Propagation, Vol. 62 , Issue 3, pp. 1445 – 1455, 2014. Number of citations:14
10. T. Abbas, F. Tufvesson:, Line-of-Sight Obstruction Analysis for Vehicle-to-Vehicle Network Simulations in a Two Lane Highway Scenario, International Journal of Antennas and Propagation, Special Issue on Radio Wave Propagation and Wireless Channel Modeling, Vol. 8, pp. 27-34, 2013. Number of citations:3
11. L. Bernado, T. Zemen, F. Tufvesson, A. Molisch, C. Mecklenbrauker:, Delay and Doppler Spreads of Non-Stationary Vehicular Channels for Safety Relevant Scenarios, IEEE Transactions on Vehicular Technology,, Vol. 63, No. 1, pp. 82-93, 2014. Number of citations:15
12. E. G. Larsson, O. Edfors, F. Tufvesson, T. L. Marzetta: Massive MIMO for Next Generation Wireless Systems, IEEE Communications Magazine, Vol. 52, No. 2, pp. 186-195, 2014. Number of citations:283
13. T. Abbas, L. Bernado, A. Thiel, C. F. Mecklenbräuker, F. Tufvesson, “Radio Channel Properties for Vehicular Communication: Merging Lanes Versus Urban Intersections”, IEEE Vehicular Technology Magazine, Vol. 8, No. 4, pp. 27-34, 2013. Number of citations:7
14. F. Harrysson, J. Medbo, T. Hult, F. Tufvesson: Experimental Investigation of the Directional Outdoor-to-In-Car Propagation Channel, IEEE Transactions on Vehicular Technology, Vol 62, issue, 6, pp 2532-2543, 2013. Number of citations:3
15. W. N. Khan, M. Zubair, S. Wyne, F. Tufvesson, K. Haneda: Performance Evaluation of Time-Reversal on Measured 60 GHz Wireless Channels, Wireless Personal Communications, Vol. 71, No. 1, pp. 707-717, 2013. Number of citations:2

16. T. Abbas, J. Kåredal, F. Tufvesson: Measurement-Based Analysis: The Effect of Complementary Antennas and Diversity on Vehicle-to-Vehicle Communication, IEEE Antennas and Wireless Propagation Letters, Vol. 12, No. 1, pp. 309-312, 2013. Number of citations:9
17. M. Zhu, G. Eriksson, F. Tufvesson: The COST 2100 Channel Model: Parameterization and Validation Based on Outdoor MIMO Measurements at 300 MHz, IEEE Transactions on Wireless Communications, Vol. 12, No. 2, pp. 888-897, 2013. Number of citations:8
18. F. Rusek, D. Persson, B. K. Lau, E. G. Larsson, T. L. Marzetta, O. Edfors, F. Tufvesson: Scaling up MIMO: opportunities and challenges with very large arrays, IEEE Signal Processing Magazine, Vol. 30, No. 1, pp. 40-60, 2013. Number of citations: 791
19. M. G. Khan, B. Sallberg, J. Nordberg, F. Tufvesson, I. Claesson: Non-Coherent Fourth-Order Detector for Impulse Radio Ultra Wideband Systems: Empirical Evaluation Using Channel Measurements, Wireless Personal Communications, Vol. 68, No. 1, pp. 27-46, 2013. Number of citations:2
20. L. Liu, C. Oestges, J. Poutanen, K. Haneda, P. Vainikainen, F. Quitin, F. Tufvesson, P. De Doncker: The COST 2100 MIMO Channel Model, IEEE Wireless Communications, Vol. 19, No. 6, pp. 92-99, 2012. Number of citations:27
21. J. Poutanen, F. Tufvesson, K. Haneda, V. M. Kolmonen, P. Vainikainen: Multi-link MIMO channel modeling using geometry-based approach, IEEE Transactions on Antennas and Propagation, Vol. 60, No. 2, pp. 587-596, 2012. Number of citations:20
22. T. Abbas, F. Tufvesson: System Identification in GSM/EDGE Receivers Using a Multi-Model Approach, International Journal on Control System and Instrumentation, Vol. 3, No. 1, pp. 41-46, 2012.
23. A. Bernland, M. Gustafsson, C. Gustafson, F. Tufvesson: Estimation of Spherical Wave Coefficients from 3D Positioner Channel Measurements, IEEE Antennas and Wireless Propagation Letters, Vol. 11, pp. 608-611, 2012. Number of citations: 1
24. W. N. Khan, M. Zubair, S. Wyne, F. Tufvesson, K. Haneda: Performance Evaluation of Time-Reversal on Measured 60 GHz Wireless Channels, Wireless Personal Communications, No. Sept., 2012. Number of citations: 2
25. C. Gustafson, F. Tufvesson: Characterization of 60 GHz Shadowing by Human Bodies and Simple Phantoms, Radioengineering, Vol. 21, No. 4, pp. 979-984, 2012.
26. J. Kåredal, N. Czink, A. Paier, F. Tufvesson, A. Molisch: Path loss modeling for vehicle-to-vehicle communications, IEEE Transactions on Vehicular Technology, Vol. 60, No. 1, pp. 323-328, 2011. Number of citations:78
27. C. Mecklenbräuker, A. Molisch, J. Kåredal, F. Tufvesson, A. Paier, L. Bernadó, T. Zemen, O. Klemp, N. Czink: Vehicular channel characterization and its implications for wireless system design and performance, Proceedings of the IEEE, Vol. 99, No. 7, pp. 1189-1212, 2011. Number of citations:128
28. S. Wyne, K. Haneda, S. Ranvier, F. Tufvesson, A. Molisch: Beamforming effects on measured mm-wave channel characteristics, IEEE Transactions on Wireless Communications,, Vol. 10, No. 11, pp. 3553-3559, 2011. Number of citations:23
29. J. Poutanen, J. Salmi, K. Haneda, V. M. Kolmonen, F. Tufvesson, P. Vainikainen: Propagation Characteristics of Dense Multipath Components, IEEE Antennas and Wireless Propagation Letters, Vol. 9, pp. 791-794, 2010. Number of citations:8
30. A. Alayon Glazunov, M. Gustafsson, A. Molisch, F. Tufvesson “Physical modeling of MIMO antennas and channels by means of the spherical vector wave expansion”, IET Microwaves, Antennas and Propagation, Vol. 4, No. 6, pp. 778-791, 2010. Number of citations:25
31. T. Santos, F. Tufvesson, A. Molisch “Modeling the Ultra-Wideband Outdoor Channel - Model Specification and Validation”, IEEE Transactions on Wireless Communications, Vol. 9, No. 6, pp. 1987-1977, 2010. Number of citations:22
32. V. M. Kolmonen, K. Haneda, T. Hult, J. Puotanen, F. Tufvesson, P. Vainikainen, ”Measurement-based evaluation of interlink correlation for indoor multi-user MIMO Channels”, IEEE Antennas and Wireless Propagation Letters, Vol. 9, pp. 311-314, 2010. Number of citations:16

33. V. M. Kolmonen, K. Haneda, J. Puotanen, F. Tufvesson, P. Vainikainen, “A dual-link capacity analysis of measured time-variant indoor channel”, Electronics Letters, Vol. 46, No. 8, pp. 592-593, 2010. Number of citations: 2
34. V.-M. Kolmonen, P. Almers, J. Salmi, J. Koivunen, K. Haneda, A. Richter, F. Tufvesson, A. F. Molisch, and P. Vainikainen, “A dynamic dual-link wideband MIMO measurement system for 5.3 GHz,” IEEE Transactions on Instrumentation and Measurement, Vol 59, Issue 4, pp 873-883, 2010. Number of citations:42
35. J. Kåredal, P. Almers, A. J. Johansson, F. Tufvesson, A. Molisch “A MIMO channel model for wireless personal area networks”, IEEE Transactions on Wireless Communications, Vol. 9, No. 1, pp. 245-255, 2010. Number of citations:11
36. S. Wyne, T. Santos, A. Singh, F. Tufvesson, A. Molisch “Characterization of a time-variant wireless propagation channel for outdoor short-range sensor networks”, IET Journal on Communications, Vol. 4, No. 3, pp. 253-264, 2010. Number of citations:7
37. T. Santos, J. Kåredal, P. Almers, F. Tufvesson, A. Molisch “Modeling the ultra-wideband outdoor channel - measurements and parameter extraction method”, IEEE Transactions on Wireless Communications, Vol. 9, No. 1, pp. 282-290, 2010. Number of citations:38
38. F. Harrysson, J. Medbo, A. Molisch, A. J. Johansson, F. Tufvesson “Efficient experimental evaluation of a MIMO handset with user influence”, IEEE Transactions on Wireless Communication, Vol. 9, No. 2, pp. 853-863, 2010. Number of citations:40
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40. A. Paier, J. Kåredal, N. Czink, C. Dumard, T. Zemen, F. Tufvesson, A. Molisch, C. F. Mecklenbräuker “Characterization of Vehicle-to-Vehicle Radio Channels from Measurements at 5.2GHz”, Wireless Personal Communications, Vol. 50, No. 1, pp. 19-29, 2009. Number of citations:70
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4. Patent applications

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3. F. Tufvesson and F. Thorsell ”Method and system for supporting the search for a mobile station”, PCT application, July 2008.
4. A.F. Tufvesson, “Hybrid UWB receiver with matched filters and pulse correlator”, U.S. patent application 20050013390

5. Open access computer programs

Administrator of, and one of the main contributors to, the open source implementation of the COST2100 channel model. Specific contributions to the multi-link concept, parameterization of indoor as well as outdoor scenarios, massive MIMO extension.

Five most cited publications

1. F. Rusek, D. Persson, B. K. Lau, E. G. Larsson, T. L. Marzetta, O. Edfors, F. Tufvesson: Scaling up MIMO: opportunities and challenges with very large arrays, IEEE Signal Processing Magazine, Vol. 30, No. 1, pp. 40-60, 2013. Number of citations: 791
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CV

Name: Fredrik Tufvesson	**Doctorial degree:** 2000-09-22
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Research education

Dissertation title (swe)

Dissertation title (en)

Design of Wireless Communication Systems -- Issues on Synchronization, Channel Estimation and Multi-Carrier Systems

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Lunds universitet, Sweden Sweden - Higher education Institutes	Elektro- och informationsteknik 107201	Torleiv Maseng

Subject doctors degree	ISSN/ISBN-number	Date doctoral exam
20203. Kommunikationssystem	1402-8662	2000-09-22

Publications

Name: Fredrik Tufvesson	**Doctorial degree:** 2000-09-22
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Gender: Male	**Employer:** Lunds universitet

Tufvesson, Fredrik has not added any publications to the application.

Register

Terms and conditions

The application must be signed by the applicant as well as the authorised representative of the administrating organisation. The representative is normally the department head of the institution where the research is to be conducted, but may in some instances be e.g. the vice-chancellor. This is specified in the call for proposals.

The signature*from the applicant*confirms that:

- the information in the application is correct and according to the instructions form the Swedish Research Council
- any additional professional activities or commercial ties have been reported to the administrating organisation, and that no conflicts have arisen that would conflict with good research practice
- that the necessary permits and approvals are in place at the start of the project e.g. regarding ethical review.

The signature *from the administrating organisation* confirms that:

- the research, employment and equipment indicated will be accommodated in the institution during the time, and to the extent, described in the application
- the institution approves the cost-estimate in the application
- the research is conducted according to Swedish legislation.

The above-mentioned points must have been discussed between the parties before the representative of the administrating organisation approves and signs the application.

Project out lines are not signed by the administrating organisation. The administrating organisation only sign the application if the project outline is accepted for step two.

Applications with an organisation as applicant is automatically signed when the application is registered.