Application

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Project site: Avdelningen för Kommunikationssystem

Information about application

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Funds applied for

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Descriptive data

Project info

Project title (Swedish)*

Angreppssätt baserat på rumslig punktprocess för storskaliga insikter i stora trådlösa nätverk

Project title (English)*

Spatial Point Process Approach for Macroscopic Insights into Large Wireless Networks

Abstract (English)*

With the advent of various densified and large-scale wireless networks, it is even humbling to concede that the last decade has seen networking community conquering mostly small-scale problems or tackling network-level problems in a heuristic fashion while, by and large, failing to illuminate macroscopic insights into network-wide performance metrics, which are indispensable to network planning and deployment. The sheer lack of any formula for key metrics and the widespread use of exhaustive simulations as the last resort categorically epitomize our limited understanding of large-scale behavior.

This study brings forward system-level performance analysis of cellular and sensor networks by leveraging spatial point process (PP) approach thus paving the way for encapsulating the average performance of a node or sensor in large-scale networks. Firstly, by exploiting ground-breaking advances in PP theory literature on new models of mathematically tractable spatial PP (2014) and tessellations which accurately capture base station deployment and cell shape, hence simplistic interference expression, we aim to investigate and devise realistic spatial models for promising network-level features in cellular networks including interference management, frequency reuse, load balancing, multi-tier access, and antenna diversity. In the meantime, ad hoc sensor networks are less prone to interference, yet more susceptible to resource depletion (e.g., energy) concentrated around sink nodes, induced by the hierarchical structure. To tackle this problem, our second mission makes unprecedented use of spatial Palm calculus, which provides general mathematical formulas relating hierarchical viewpoints among different classes of sensors and nodes. We thereby set forth exploration of this hitherto uncharted territory to provide holistic system-level insights into the relations between traffic engineering, lifetime, data fusion, and densities of sensors and nodes, along with a novel performance metric in energy harvesting sensor networks.

Popular scientific description (Swedish)*

I och med tillkomsten av olika typer av förtätade och småskaliga trådlösa nätverk är det beklämmande att betänka att under det sista årtiondet har forskningsvärlden främst tagit sig an småskaliga problem och nätverksfrågor utgående från ett heuristiskt angreppsätt och samtidigt i princip misslyckats med att belysa makroskopiska insikter avseende prestandaegenskaper på nätomspännande nivå, vilka är ovärderliga för nätverksplanering och driftsättning. Den totala avsaknaden av formulerade nyckelvärden och den utbredda användningen av uttömmande simuleringar som sista utväg avspeglar tydligt vår begränsade förståelse av storskaliga beteenden.

Detta arbete för fram prestandaanalys på systemnivå av cellulära och sensornätverk baserat på rumsliga punktprocesser och bereder därigenom väg för bestämning av genomsnittlig prestanda hos en nod eller sensor i storskaliga nätverk. Till att börja med, genom att dra nytta av banbrytande resultat inom punktprocessteori avseende nya modeller för matematiskt hanterbara rumsliga punktprocesser (2014) och tesselationer som på ett korrekt sätt speglar placering av basstationer och cellgeometri, och därmed förenklade inteferensmönster, avser vi att undersöka och ta fram realistiska rumsliga modeller för relevanta grunddrag i cellulära nätverk, inkluderande interferenshantering, frekvensåteranvändning, lastbalansering, flernivååtkomst samt antenndiversitet. Samtidigt är ad-hoc sensornätverk mindre känsliga för interferens men känsliga för resursförbrukning (energi, till exempel) koncentrerat runt de utgångsnoder som bildas genom den hierarkiska strukturen. För att angripa detta problem använder vi rumslig Palmkalkyl på ett helt nytt sätt, vilket ger allmänna matematiska relationer som relaterar hierarkiska synvinklar mellan olika klasser av sensorer och noder. Vi initierar därigenom utforskning av detta hittills ogenomsökta område för att uppnå holistiska insikter på systemnivå inom relationer mellan trafikstyrning, livslängd, datafusion samt sensor- och nodtäthet, tillsammans med nya prestandamått inom energisamlande sensornätverk.

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 > 20204. Telekommunikation

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

Keyword 1*

cellular network

Keyword 2*

ad hoc sensor network

Keyword 3*

point process theory

Keyword 4

Palm calculus

Keyword 5

stochastic geometry

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*

None.

The project includes handling of personal data

No

The project includes animal experiments

No

Account of experiments on humans

No

Research plan

Spatial Point Process Approach for Macroscopic Insights into Large Wireless Networks

Abstract

With the advent of various densified and large-scale wireless networks, it is even humbling to concede that the last decade has seen networking community conquering mostly small-scale problems or tackling network-level problems in a heuristic fashion while, by and large, *failing* to illuminate macroscopic insights into network-wide performance metrics, which are indispensable to network planning and deployment. The sheer lack of any formula for key metrics and the widespread use of exhaustive simulations as the last resort categorically epitomize our limited understanding of large-scale behavior. This study brings forward system-level performance analysis of cellular and sensor networks by leveraging ***spatial point process*** (PP) approach thus paving the way for encapsulating the *average* performance of a node or sensor in large-scale networks. Firstly, by exploiting ground-breaking advances in PP theory literature on new models of *mathematically tractable* spatial PP (2014) and tessellations which accurately capture base station deployment and cell shape, hence *simplistic interference expression*, we aim to investigate and devise **realistic spatial models** for promising network-level features in cellular networks including interference management, frequency reuse, load balancing, multi-tier access, and antenna diversity. In the meantime, ad hoc sensor networks are less prone to interference, yet more susceptible to resource depletion (*e.g.*, energy) concentrated around sink nodes, induced by the hierarchical structure. To tackle this problem, our second mission makes unprecedented use of ***spatial Palm calculus***, which provides general mathematical formulas relating hierarchical viewpoints among different classes of sensors and nodes. We thereby set forth exploration of this hitherto uncharted territory to provide **holistic system-level insights** into the relations between traffic engineering, lifetime, data fusion, and densities of sensors and nodes, along with a *novel performance metric* in energy harvesting sensor networks.

I. Introduction, Motivation, and Main Objectives

The current and future **cellular networks** are facing fundamental challenges due to dense or additional infrastructure, *i.e.*, base stations (BS) and relays, and users deployed on a massively large-scale[1]. They are envisioned to overcome these challenges by, for example, network-level interference management, frequency reuse, dynamic load balancing, multiple antenna optimization, as well as new heterogeneous structure (also known as HetNet) comprising macro and small cells (picocells), all of which are key enabling technologies for higher throughput in densified networks. In the meantime, even with ever growing demand on a broad range of emerging applications in **ad hoc sensor networks** deployed on vast areas such as environmental monitoring, smart metering in power grids, and traffic monitoring in intelligent transportation systems, the networking community has not shed enough lights on the ever increasing list of generic network-level aspects such as traffic engineering (spreading and routing), data fusion (aggregation and compression), lifetime maximization, sleep mode, and energy harvesting, *apart from* extensive research on coverage probability[2] (*e.g.*, a seminal paper by Liu and Towsley [12]).

In both categories of wireless networks, the vast volume of past research efforts have been focused on the **atomistic approach**. That is, researchers have been conquering mostly small-scale problems amenable to tractable analysis or addressing a few network-level issues often in an ad-hoc fashion, *e.g.*, solving formidably complex optimization problems by heuristic algorithms inspired by simulation/experimental results[3], while conspicuously failing to deliver deeper understanding of network-wide performance metrics and their interrelations, which are direly needed for massive-scale network-level planning and provisioning. Once such system-level *formulas* are worked out, albeit arduously, they have the potential to open up entirely new opportunities for diverse macroscopic optimization problems tailored to each specific network, *e.g.*, maximizing total throughput in heterogeneous cellular networks and minimizing delivery time for time-critical messages in ad hoc sensor networks. Therefore, one might dare to ask the following pertinent yet humbling question:

[1] The scope of this study is limited to cellular and ad hoc sensor networks, not least because they are existing yet open to forthcoming further evolutions in the near future, thus reducing the risk of the study.

[2] The term 'cover' used in sensor networks refers to one or more sensors covering a point while the same term in cellular networks refers to the desired signal at a point being successfully decoded from 'interference plus noise'.

[3] There exists a perennial dilemma of a *circular reference* between 'part-wise optimization' and 'system-level analysis'. This study argues that networking community has spent a disproportionate amount of efforts on the former, largely neglecting the latter.

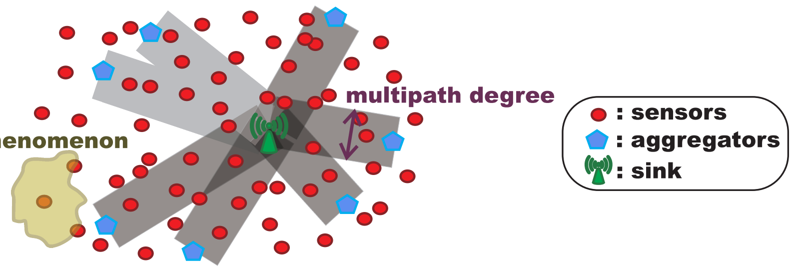

Fig. 1: A large-scale sensor network to detect or monitor spatial phenomena where the degree of multipath between an aggregator and its closest sink is denoted by the width of the strip stretching between them which embodies the extent of traffic engineering.

Q: *"What is the use of those disparate sophisticated mechanisms which cannot delineate the relations between (i) network-level performance and (ii) system parameters such as the number of nodes?"* To do justice to the networking community, relevant methodologies for stochastic analysis of networks spanning over huge space had been in their infancy until the mathematical advances were pieced together into books, *e.g.*, [2] by François Baccelli and Bartłomiej Błaszczyszyn (2010), and [9] by Jean-Yves Le Boudec (2010), which are very rarely used in engineering schools in Europe (not to mention Sweden) in spite of *arduously* engineer-friendly approach in [9].

To better understand the **schism** between the *atomistic* approach in the literature and the **holistic** approach in this study, let us consider a large-scale ad hoc sensor network in Fig. 1 consisting of sensors, aggregators, and sinks randomly scattered over a vast area with different node **intensities** where the detection information of sensors covered by the spatial *phenomena* should reach a sink such that the **performance metric** of interest, *i.e.*, network lifetime, is maximized. Here aggregators may aggregate information from sensors in close proximity, which is in turn forwarded to the closest sink through multiple paths between them, *i.e.*, the multipath *strip* whose width represents the degree of multipath routing. It can be intuitively seen that there are several complicated tradeoffs: (i) as the intensity of sinks decreases (↓) or as the size of phenomena increases (↑), more strips overlap with each other, leading to higher energy burden on nodes around the sink, which necessitates higher multipath degree (↑), *i.e.*, wider strip; (ii) however, excessive multipath degree (↑↑) incurs 'detours' of traffic which counterbalances its benefit of spreading energy burden; (iii) as the intensity of aggregators decreases (↓), there is more traffic between each aggregator and the sink, which in turn necessitates higher multipath degree (↑) in order to maintain the same network lifetime. In order **to deploy such a sensor network** on a vast area, engineers must be equipped with mathematical formulas which shall not only **corroborate** our aforementioned intuitive observations but also **quantitatively encapsulate** these interwoven tensions thereby making it possible to design and improve the network by optimally adjusting main parameters including node intensities. In order to meet the need for such formulas, it is of central importance to delineate system-level behavior by ***undertaking a holistic approach***, which constitutes our main motivation.

The **sheer lack** of *system-level mathematical formulas* categorically substantiates the schism between the two approaches. For macroscopic planning and deployment of *real* large-scale wireless networks, engineers and researchers still largely rely on exhaustive, and very often infeasible, simulations and on-site experiments. Even worse, most simulations are run on proprietary simulators, which makes it extremely difficult to *verify* their veracity and to *compare* the huge volume of simulation results with the others. Therefore, in order to directly confront with these fundamental challenges, this study brings forward a radical rethink to garner macroscopic insights therein by leveraging ***spatial point process (PP)*** theory, which is **the only state-of-the-art methodology** to capsulize network-wide interactions between wireless nodes in a formal manner, thus extending the boundaries of research themes in the field (See also Sections V and VIII). More specifically, its lesser-known branch, called ***spatial Palm calculus***[4], provides not only (i) **smooth aggregation** formulas, whose non-spatial versions are analogous to the famous Little's formula, but also (ii) **relational** formulas, whose far-reaching implications in analyzing hierarchical wireless networks are even enlightening (non-spatial versions are referred to as "smooth" and "ordinal" formulas in

[4]Original (non-spatial) Palm calculus was named after the great Swedish mathematician, **Conrad Palm (1907-1951)**, whose thesis at **KTH Royal Institute of Technology** in 1943 laid the foundation for PP approach to queuing theory. He is arguably the most famous Swedish mathematician along with Harald Cramér. The PI has been using and teaching the theory (See Sec. IX).

[6]). The distinctive **novelty of this study** vis-à-vis previous spatial PP approaches lies in (i) timely application of recent **ground-breaking advances** in PP theory (Sec. III) which have received a huge surge of attention since last year (2014) due to its remarkably enhanced accuracy in approximating aggregate interference in generic wireless networks (Sec. IV) and (ii) revisiting *Palm calculus*, whose spatial version has **unparalleled profound implication** and turns out to be instrumental in **relating performance indicators** in complex hierarchical networks, thereby paving the way for our expansion of system-level insights into the unexplored territories of sensor networks[5] (Sec. V).

II. Survey of the Field: Spatial PP Approach in Networking

In plain words, PP is a random process consisting of events occurring at points, for example, arrival events in a system of queues. Rather ambiguous distinction between PP theory and queuing theory is the greater focus of the former on the perspective of events (*e.g.*, arrival events). In other words, PP theory is founded upon the principle of **conditioning the occurrence of an event** at a point in time (or a point in space in case of a spatial PP). Palm calculus provides not only a mathematical edifice of concepts and notations on which these conditional probabilistic expressions are formally defined but also a collection of new theorems which are built on top of those expressions[6]. For example, one of several key formulas, **Palm inversion formula**, states an astonishingly simple fact: **time average** of a random process is equal to its **inter-event average**, *i.e.*, the average over two consecutive events. Here, the contrast between this **highly intuitive and mathematically tractable** concept of inter-event average and the impossibility of conditioning an event at a point due to the **limitation of conventional notations** is **astounding**. Its immense impacts on analysis of event-driven systems were epitomized by Le Boudec and Vojnović [10] who received IEEE Infocom 2005 Best Paper Award. They used Palm calculus to resolve a longstanding issue on pathological behavior of random waypoint models.

A. Cellular Networks: Spatial Poisson PP Models

The seemingly simple transition from PP theory to spatial PP theory, *i.e.*, changing the domain from time to multi-dimensional Euclidean space, necessitated a substantial volume of new theoretical results which were finally compiled into the book [2] in 2010 by François Baccelli and Bartłomiej Błaszczyszyn. While the networking community showed sporadic interests in the spatial PP approach, it seems to be fair to say that the paper by Haenggi *et al.* [7] in 2009 dramatically rekindled the flames of interests in the approach where spatial **Poisson PP** was used to model wireless node (*e.g.*, base station) deployment to yield a tractable *total interference* expression measured at a point over a network, which paved the way for deriving key performance metrics in cellular networks. Among several research efforts mainly conducted by the two groups of Haenggi and Baccelli, Andrews *et al.* [1] in 2011 derived *tractable* coverage probability expressions under general fading and path loss models where BSs are scattered on an area in a completely random and independent fashion, *i.e.*, according to a Poisson PP. It is rather astonishing that such network-wide formulas even for the case of the Poisson PP had been **notably absent** in networking field before this work.

B. Ad Hoc Sensor Networks: Lack of System-level Models

Due to the small amount of sensing information generated in typical sensor networks, the role of interference therein is considerably diminished. Therefore, the aforementioned spatial PP models in cellular networks, which were used to capture aggregate interference, have not attracted much attention in ad hoc sensor networks (See Sec. V for more discussion). In fact, it is important to distinguish (i) **another spatial PP models** in the literature of sensor networks [12] used for analysis of coverage probability from (ii) those spatial PP models in our study which exploit sophisticated mathematical concepts in PP theory and Palm calculus to compute various performance indicators of an average node or an average sensor. Here the coverage probability in sensor networks, *i.e.*,

[5]**No work** except Baek and de Veciana [4] has used spatial Palm calculus for analyzing ad hoc sensor networks (See Sec. V).

[6]It is impossible to define them without Palm calculus because the probability of the occurrence of event A at a point in continuous time or space is zero, *i.e.*, $\mathsf{P}(A) = 0$, which renders the conditional probability $\mathsf{P}(B|A) = \mathsf{P}(B \cap A)/\mathsf{P}(A)$ **undefinable**.

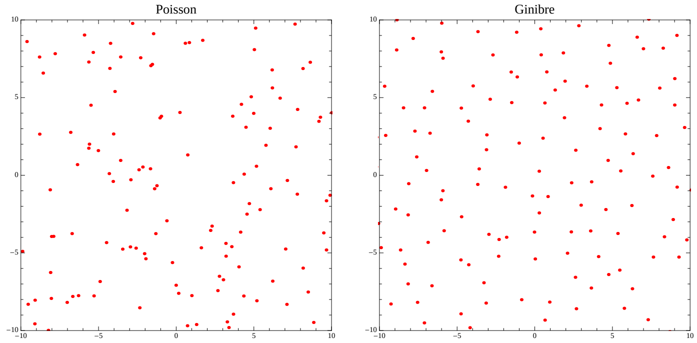

Fig. 2: Poisson (left) and Ginibre PPs (right). Ginibre PP accounts for repulsion between nodes. **Courtesy of the authors of [13]**.

the probability that a point is covered by one or more sensors, is also completely different from that used in cellular networks, *i.e.*, the probability that the signal-to-interference-noise-ratio (SINR) at a point exceeds a certain threshold (See also Footnote 2). In other words, spatial PP models in sensor networks so far have been mainly focused on the *total sensing area* (equivalent to coverage probability in sensor networks) covered by the sensor network.

Consequently, putting all the related works into perspective, system-level analysis in ad hoc sensor networks, which comprehensively encompasses and delineates diverse performance metrics of an average sensor and the intensities of different classes of nodes (*e.g.*, see Fig. 1), has been **wholly lacking** except the research efforts on total sensing area [12] which do not make use of sophisticated mathematical concepts in spatial versions of PP theory and Palm calculus.

III. Ground-Breaking Advances and State of the Art in PP Theory

Notwithstanding the tractable interference expressions in [1] incorporating general fading and path loss models, (i) the Poisson PP modeling of BS distribution and (ii) associating each user to the closest BS, also known collectively as **Poisson/Voronoi tessellation**, received severe criticisms. In actual cellular networks, there exist various degrees of repulsion between BSs, whereas Poisson law implies that BSs can be **unrealistically close** to each other, which essentially renders the total interference expression impractical. Moreover, the Voronoi tessellation, where each user is tied to the nearest BS even if other BSs are more favorable for the user, turns out to be **too restrictive** in real networks composed of largely heterogeneous BSs. Lastly, the **great methodological irony** is that the versatile power of Palm calculus was, by and large, *absent* in the past spatial PP approach because the Poisson PP model, hence its independence property, effectively makes Palm calculus dispensable in the end[7]. These issues have been addressed in the following ground-shattering papers:

- ⋆ **Miyoshi and Shirai [13] (2014)**: This paper introduced a new PP, called **Ginibre PP**, to networking community, which *not only accurately but also tractably encapsulates* actual BS deployment and the correlation therein, hence interference. Here Palm calculus is instrumental in deriving tractable expressions. The Ginibre PP is one of the *determinantal* point processes (due to its intensity measure given in terms of determinants), which are used to model fermions in quantum mechanics and account for the repulsion between particles. Samples of Poisson and Ginibre PPs are shown in Fig. 2. Its generalized version [11] encompasses Poisson PP as its limiting regime.
- ⋆ **Møller [14] (1992)**: The author investigates **Johnson-Mehl tessellation** capturing *heterogeneity* of nodes (*e.g.*, BSs), and derives tractable formulas. As this tessellation allows nuclei (BSs) to start growing their grains (cells) at different times, the resulting cells are equivalent to the case where BSs have different transmission powers and each user is associated with the BS providing highest received pilot power. Therefore, it is **the only model** capturing heterogeneous powers. Although there are other tessellations in the literature of spatial PP theory, the two properties, *i.e.*, (i) the same growing speed of grains and (ii) different starting times, make this tessellation the only model correctly describing heterogeneous transmission powers of BSs. Also, it is a natural extension of the conventional Voronoi tessellation. To enhance mathematical tractability, **Laguerre tessellation [8] (2008)** can also be considered as a reasonable approximation.

[7] Under Poisson law, the occurrence of an event at a point in space has no effect on other events due to the **complete independence**.

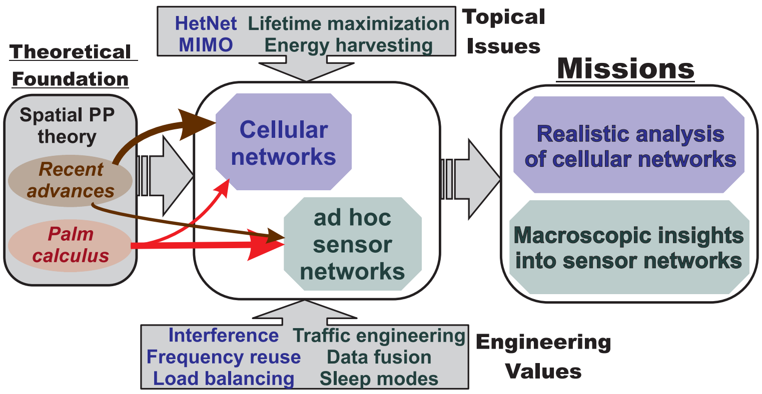

Fig. 3: An overview of two missions in this study in terms of theoretical foundation, topical issues, and engineering values.

Our well-timed study aims at (i) leveraging these two major advances to establish **realistic spatial PP** framework incorporating regularity of the BS configuration and diverse properties of wireless nodes and (ii) instating the spatial version of Palm calculus as the **universal methodology** opening up **unprecedented horizons** for relating and intertwining hierarchical viewpoints of different classes of nodes to delve into **system-level insights and formulas** in ad hoc sensor networks.

IV. First Mission: Realistic Performance Analysis of Cellular Networks

This study responds to *fundamental challenges of highest impact*, posed by future evolutions of two existing major wireless networks, while ensuring that main research ideas are based on solid theoretical foundation underpinned by recent breakthroughs in probability community, thus being risk-averse and massively **elevating its feasibility**. An overview of two missions is shown in Fig. 3. In the first mission, one objective is to lay theoretical groundwork for realistic spatial PP models of cellular networks by heavily exploiting mathematical flexibility gained by Ginibre PP [13] and new tessellations [8], [14]. The groundwork also serves as the cornerstone of the second objective.

- Producing tailored analytical results in realistic spatial PP models: As depicted in Fig. 2, Ginibre PP **superbly** represents BS configuration. It is shown [11] that this new PP fitted to real BS configurations is remarkably accurate vis-à-vis Poisson PP (See Sec. VI-A for a detailed discussion). Here, hitherto a dispensable tool, Palm calculus is finally **indispensable** for deriving mathematically tractable expressions for key metrics. Combining our Palm theoretic grasp of the Ginibre PP with the expression power of new tessellations [8], [14] and tractable results thereof, we aim at developing new *tractable analytical representations* for various key indicators and simplifying them into approximate expressions direly needed for macroscopic analysis of cellular networks.

Rather surprisingly, the overall pace of research efforts devoted to applying spatial PP approach in wireless networks since the seminal paper [7] in 2009 has been moderate if not slow. For the simpler case of *stylized* Poisson PP model, the **coverage probability expression** (equivalent to SINR distribution) incorporating general fading and path loss models was derived in the the paper [1] published in late 2011. This undesirably slow progress is partly because networking community has not been familiar with PP theory and its cornerstone, *i.e.*, Palm calculus, which contains **esoteric theoretical treatment** to circumvent zero probability of the occurrence of an event at a point (See Footnote 6). Our second objective is to accelerate diminutive research efforts on this front:

- Wide application of realistic spatial PP approach to practical scenarios: Networking community undertook the Ginibre PP approach very recently since the paper [13] in 2014, whereas new tessellations [8], [14] **have not been espoused** yet. For instance, 'the distance plus different weights' concept of Johnson-Mehl tessellation (Sec. III) lends itself to incorporating **different transmission powers** of BSs. Rather unexpectedly, there has been **no attempt** in spatial PP approach to analyze heterogeneous networks where each user is associated with the BS providing the largest pilot power (as in 3GPP). Leveraging these two ground-shattering advances which bring in new frameworks *elegantly capturing* (i) actual BS deployment and (ii) heterogeneity of BSs in various senses, this study sets out to realistically *investigate prospective network-level features* in future cellular networks including downlink/uplink interference management/coordination, frequency reuse, load balancing, multi-tier access (HetNet), antenna diversity (MIMO), and opportunistic scheduling.

Now that new spatial models including Ginibre PP (2014) and new tessellations are opening up unprecedented new horizons for **system-level formulas** representing realistic performance of cellular networks as compared with *stylized* models of Poisson PP and Voronoi tessellation which yielded **merely insights**, this study will bring about new theoretical and pragmatic advances, paving the way for large-scale network planning without resorting to exhaustive, and oftentimes infeasible, simulations. Also, from a theoretical perspective, since Ginibre PP lends itself to *simplistic Palm expressions* in spite of dependency between points (as in real BS deployment), it is imperative that Palm calculus is properly used to derive tractable expressions of performance indicators.

V. Second Mission: Macroscopic Insights into Ad Hoc Sensor Networks

While predominantly non-European research efforts are setting about analyzing large cellular networks where the aggregate interference at a point therein can be described by simple expressions founded on Poisson PP models, thereby fulfilling academic obligations to alleviate the lack of network-level insights thereof, system-level analysis in sensor networks has remained mostly uncharted territory. Since the majority of sensor networks are *far less prone to interference* due to intermittent (if not rare) sensing and transmission of information, the total interference expressions, derived through Campbell's formula, are no longer useful. Thus the methodological value of the above approach underpinned by **network-wide aggregation or summation**[8] of Campbell's formula is drastically depreciated in sensor networks. On the other hand, there are **relational formulas** gracefully unraveling the relations between intricately interwoven **viewpoints** and events (*i.e.*, points of a PP), which are the holy grail of spatial version of Palm calculus. Our first objective is to leverage them to tackle network lifetime maximization problems depicted in Fig. 1:

- Spatial PP approach to maximizing network lifetime in large sensor networks: As revealed by Baek and de Veciana [4] who considered a more complex version of the problem shown in Fig. 1, versatility and universality of Palm calculus have great potential to illuminate system-level insights into the pathological issues of **hierarchical ad hoc sensor networks** where sensors, aggregators and sinks are randomly deployed with their respective intensities and sequentially forward sensing information from low echelons to higher ones, thus incurring severe resource depletion concentrated around high class nodes, *e.g.*, sinks. There is no other work adopting similar techniques **in the entire networking field**, not to mention sensor networks. As a matter of fact, these techniques are **exceptionally rare in any field**. To investigate this largely uncharted territory, we aim at formulating and solving more sophisticated *network lifetime maximization problems incorporating various network-level mechanisms* such as traffic engineering (routing), myriads of data fusion (aggregation and compression) methods, and practical power saving sleep modes.

As for **theoretical feasibility**, the overall approach in the above objective is highly promising. Baek and de Veciana [4] used nothing but the main result, called **Palm inversion formula**[9] [2] (2010), where the key technique for the analysis is to recursively relate perspectives of different classes of nodes, moving from the bottom of the hierarchy (*i.e.*, a typical sensor) to the top of the hierarchy (*i.e.*, a sink node or an aggregator node). The unparalleled profound implication of ***spatial Palm calculus*** enables us to **simplify the global average of a performance metric of a typical sensor to its local average** associated with a higher-class node, either a sink or an aggregator, while **allowing all kinds of dependencies** between regions and the local performance metrics associated with different higher-class nodes. Thus the energy consumption of a typical sensor can be estimated from the viewpoint of a higher-class node. This technique turns out to be universally applicable and also crucial in puzzling out complicated lifetime maximization problems shown in Fig. 1 (Recall all the complex interwoven tradeoffs in Sec. I). One might venture to say that Palm calculus has been **wrongfully sacrificed for the notational scaffolding** of mathematics (See Footnote 6).

In the meantime, with the advent of energy replenishing sensors which harvest energy from the environmental sources (*e.g.*, solar power) to *perpetuate* their operation, we set forth an entirely new performance metric, **depletion probability**, to represent our radically new interests in the number

[8] Campbell's formula is merely a **rudimentary** result stating: the average sum of a function $f(\cdot)$ over points generated by the PP is equal to the integral of $f(\cdot)$ with respect to the intensity measure of the PP. Simply put, **average sum is replaced by integral**.

of sensors *alive* or *resurrected* at an arbitrary time, rather then their effectively infinite lifetime. This study delves into this metric which is also amenable to the techniques of spatial Palm calculus:

- Spatial PP model for energy depletion probability in energy harvesting sensor networks: In energy harvesting sensor networks, dead nodes are occasionally resurrected by environmental power sources which fluctuate from hour to hour. A pertinent question is **how much fraction of the sensors operate on average** given stochastically changing environmental energy sources. Combining spatial PP models with energy buffer models, we set out to establish a holistic framework to gain system-level insights into this outstanding problem.

Remarkably, while the spatial Palm calculus is the **irreplaceable mathematical apparatus** not only effectuating all these analyses but also leading and paving all the way to **unimaginably refined results** illuminating system-level tradeoffs (including the reduced versions in Fig. 1), it **has not made its presence** anywhere in networking field except in the above paper [4]. As discussed in Sec. II and Footnote 6, the first reason is perhaps that the construction of Palm calculus is immensely complex, which makes itself far less accessible to engineers. Secondly, there are marked, potentially even baffling, distinctions in interpreting and applying key formulas of spatial and non-spatial versions of Palm calculus, as discussed in Sec. VI-B. For instance, in the context of a sensor network, *spatial Palm inversion formula* relates (i) the **spatial average** (formally, expectation) of a performance metric to (ii) **local average** (intra-region average), *i.e.*, the average over a local region which is administered by a higher class node where all nodes eventually deliver their sensing information to the higher class node. Note that the local average is quite often easily manipulated.

Last but not least, the recent advances in Sec. III exert strikingly distinctive impacts upon hierarchical sensor networks, which will also be exploited in the above two objectives. That is, the Ginibre PP can encapsulate more regular deployment of aggregators and sinks, which has the potential to **alleviate concentration of traffic**, hence the energy burden, surrounding them. Also, a sensor may prefer (i) an aggregator close to a sink to (ii) the aggregator closest to the sensor. This sophisticated **load balancing** mechanism can be captured by the new tessellations.

VI. Principal Methodologies of the Study

The representative methodologies espoused in this study, *i.e.*, spatial PP theory and spatial Palm calculus, were established only recently by [2] in 2010 and even their non-spatial versions [3] have not been familiar to researchers in networking field. In this section, we briefly review and expatiate on these methodologies along with recent advances to demonstrate the solid theoretical foundation and methodological novelty of the study.

A. Modeling Accuracy and Tractability of Ginibre PP

Real BS deployments exhibit repulsion between the BSs, which means that they are distributed more regularly than the realization of a Poisson PP (See Fig. 2) yet less regularly than a grid model. To bridge the gap of these modeling inaccuracies, the Ginibre PP (See Fig. 2) and its generalized version were introduced by [13] and [11] in 2014 which are used to model repulsion between fermions in quantum mechanics. Since our first mission in cellular networks is to study and apply spatial PP models for performance analysis of large cellular networks, it important to ensure the Ginibre PP model incorporates real BS locations in a mathematically tractable manner.

To address these issues, Li *et al.* [11] showed that the generalized version of the Ginibre PP model, which encompasses Poisson PP as its limiting regime, yields analytically **tractable expressions** of several fundamental metrics including interference distribution. It is remarkable that the derivation of these tractable expressions is greatly facilitated by the **simplistic Palm** expressions of Ginibre PP. At the same time, the coverage probabilities of two data sets (in Houston and Los Angeles) **very closely match** with those of Ginibre PP model over a broad range of signal-to-interference ratio (SIR) threshold. These two promising findings show **enormous potential** of the generalized Ginibre PP model for developing more useful analytical results including new performance metrics and applying those tailored results for investigating network-level features (*e.g.*, interference coordination and frequency reuse) in large-scale cellular networks, which constitute the major part of our first mission.

[9] Putting all formulas into perspective, there are two *lineages* in Palm calculus, *i.e.*, Campbell's and Palm inversion formulas, with starkly different implications. Both can be **"very artificially"** (**Pierre Brémaud** [6]) derived from Miyazawa's law (1983).

B. Implication of Spatial Palm Calculus: Spatial Average to Local Average

In light of the close connections between our second mission in ad hoc sensor networks and Palm calculus, it is necessary to understand its versatility. Among its several relational formulas including Neveu's exchange formula and Wald's identity, the principal result, *i.e.*, Palm inversion formula (See, *e.g.*, [9, Chapter 7] and [3, Chapter 1]), relates the ***time average*** of a probabilistic expression to its ***inter-event average***. Formally, it states that the time average of an expression $X(t)$ (*e.g.*, throughput or mobile speed) is equal to its inter-event average, *i.e.*, frequency of occurrence of an event multiplied by the integral of the expression $X(t)$ over the interval between two events, where the latter is a Palm expression due to the condition on the occurrence of the first event. Note that the second event in the integral is still probabilistic.

Akin to the original Palm inversion formula, its spatial version (See, *e.g.*, [2, Chapter 4]) states a strikingly simple yet widely applicable mathematical fact: the ***spatial average*** (global average) of a probabilistic expression is equal to its ***local average***. More importantly, the average of whichever probabilistic expression can be replaced by a much more tractable expression, *i.e.*, the local average. As such, this relational formula paves the way for deriving **tractable performance indicators** in large-scale hierarchical networks which are composed of multiple regions (cells), each of which is administered by a high-class node, *e.g.*, a sink node. Last but not least, another equally powerful property of Palm calculus, **absence of independence assumptions**, can be interpreted as follows:

(i) the shape and size of a region are allowed to be **dependent** on those of another region;
(ii) the performance metric of a region is allowed to be **dependent** on that of another region.

That is, spatial Palm calculus ***eliminates independency assumptions*** of all kinds, thereby lending itself to analyzing realistic networks with all kinds of dependencies and interactions between regions.

VII. Collaboration with Other Researchers

Starting from the PI's visit to François Baccelli, we will establish other collaborations to stimulate diverse research ideas. As mentioned in Sections II and V, the lion's share of research efforts in spatial PP approach in networking field have been conducted in USA, which are spearheaded by **François Baccelli** in University of Texas at Austin and **Martin Haenggi** in University of Notre Dame. Apart from the two prominent figures in USA, a few researchers in *probability community* undertook the spatial PP approach for analyzing cellular networks. Among them, **Naoto Miyoshi** in Tokyo Institute of Technology, Japan, and his colleagues have been actively churning out remarkable papers including the ground-breaking work [13] which metaphorically *excavated* Ginibre PP in 2014 from the massive volume of papers in probability community. As such, we are planning to make **multiple short visits** to the aforementioned institutions including University of Texas at Austin. Since theoretical research can be produced by short visits followed by various communication methods, this type of collaboration is suitable for creating synergy effects.

VIII. Conclusion: Significance and Feasibility of the Study

In the realm of theoretical field of networking, Sweden has maintained a highly selective stance even as compared with other European countries which have taken relatively supportive stances, expending research efforts into a few **highly influential** and fundamental topics, *e.g.*, adoption of mean field theory for interacting objects in networks (See references in [PI2]) which was pioneered by researchers mostly in Europe. Moreover, spatial PP approach in wireless networks, which is the only state-of-the-art methodology with high potential to enlighten our deeper understanding of large-scale networks, thereby making it possible to deploy such networks in reality, has been adopted largely by researchers in USA[10], thus **calling for our research initiatives** in strengthening fundamental research with potential for far-reaching effects.

The spatial PP approach not only brings in **entirely new methodologies** for modeling diverse aspects of large wireless networks (*e.g.*, interference, cell shape in cellular networks and spatial hierarchy in ad hoc sensor networks), but also has the potential to **radically redefine** the principal roles of network-level research efforts in wireless networks, which have so far been rather diminutive,

[10]Ironically, the two researchers in USA, who are spearheading the approach, worked in Europe for the best part of their life.

partly due to their atomistic approaches (See Sec. I) and inevitably stylized assumptions (*e.g.*, the conspicuous absence of SINR model) espoused therein for mathematical tractability. At the same time, in retrospect, network-level performance analysis of large wireless networks has been hindered mainly by the lack of suitable methodologies. Since wireless nodes are nothing but (correlated or uncorrelated) points scattered over a vast space according to a probability distribution, spatial PP theory is **the only methodology** to mathematically summarize (*e.g.*, Campbell's formula) and relate (*e.g.*, Palm inversion formula) their network-wide interactions in various fashions (See Sec. V). Simply put, it is the ***very veritable theoretical lens*** through which large wireless networks should be analyzed. Our study is a full-scale foray into this uncharted, and often **mathematically treacherous**, territory which shall illuminate system-level insights into large-scale wireless networks.

To ensure that this research materializes, we have concocted its two missions in Sections IV and V where the challenging aspects of the outstanding problems are juxtaposed with meticulously thought-through **feasibility** of two missions in terms of (i) *topicality* of research themes, (ii) solid *theoretical foundation*, (iii) ground-shattering *recent advances* in spatial PP theory instrumental in developing realistic spatial models of wireless networks, (iv) *utilization of versatile techniques* of lesser-known spatial Palm calculus (**Recall Footnote 4**), and (v) a novel *performance indicator* arising from a prospective feature of sensor networks.

IX. Merits of the Principal Investigator and Previous Results

Creativity & Intellectual Skills: The PI of this study has shown his *creativity in a unique way*. Rather than tackling more manipulatable problems in networking field, he boldly confronted with **notoriously challenging** problems which had been *outstanding for many years* in networking community. Most remarkably, he dared to question the validity of so-called *Bianchi's formula*[11] which is *de facto* standard tool for analyzing Wi-Fi (IEEE 802.11) medium access protocol, published in IEEE Trans. on Information Theory [PI2] (in **CV and Publications**) in 2012, where he countered the formula by discovering a counterexample and derived a new *simplistic* condition validating the Bianchi's formula. Secondly, in [PI1] published IEEE Trans. on Information Theory, he also established the power-law principle of the delay distribution in Wi-Fi networks which had tantalized and even **puzzled** numerous researchers who could not show but merely conjectured the seemingly intuitive fact. To reclaim the beauty of mathematical simplicity, he leveraged the expression power of **PP theory** for analyzing the backoff processes.

Research Excellence & Independence: Throughout these two notable achievements, the PI also demonstrated his *intellectual competence* by making extensive use of the state-of-the-art techniques in *mean field theory* and *PP theory*[12] respectively for [PI2] and [PI1]. He has also **first-authored** several papers in the **most prestigious journals** in the field, *i.e.*, IEEE Trans. on Information Theory and IEEE/ACM Trans. on Networking [PI1], [PI2], [PI3]. Apart from aforementioned intellectual skills, he also proved a generalized version of Aumann-Shapley price in [PI3], which is the key formula in *coalition game theory* under the mean field regime.

International Collaboration & Mobility: The PI worked with Jean-Yves Le Boudec at EPFL, Switzerland, *IEEE Fellow*, who literally pioneered several new research methodologies in the field such as *mean field theory* and *network calculus*. More importantly, the PI has been **invited to visit François Baccelli** in University of Texas at Austin, USA, for about one month starting from April 2015[13]. François Baccelli **pioneered spatial PP theory approach** for the first time across all fields including networking field and has been actively conducting the lion's share of the research efforts. His lifelong achievements in many research topics were lately recognized by 2014 ACM Sigmetrics Achievement Award and also celebrated by a special conference dedicated to him in Paris in January 2015 which was attended by many dignitaries in the field.

Supervision & Traning Skills: The PI made a significant contribution to [PI4] and its conference version published in IEEE Infocom 2013, which substantially helped the first author of [PI4] who received Ph.D. in KAIST, South Korea, to get a postdoc position abroad at KTH, Sweden. Also,

[11] The original seminar work by G. Bianchi [5] has been cited **7230 times** as of March 2015, according to Google Scholar.
[12] The PI also applied Palm calculus in [PI4] for *functional* optimization of energy-efficient Wi-Fi access point detection schemes.
[13] François Baccelli has covered the local & hotel expenses for the one-month stay.

TABLE I: A Detailed Implementation Plan. Abbreviations in time fields, *e.g.*, Q2 Y3, denote quarters and years.

Mission 1: Realistic Performance Analysis of Cellular Networks					
Action steps	Responsible	Time		Methodology	Deliverables, Implementation
		Start	End		
Literature/subject study workshop paper **PI-led conference paper**	PI, PHD1	Q1 Y1	Q4 Y1	Ginibre PP New tessellations Spatial PP theory Spatial Palm calculus Large deviation theory	1 workshop paper 3 conference papers 2 journal papers
Gathering ideas brainstorming	PI, PHD1	Q1 Y2	Q2 Y2		
Writing and publishing conference papers	PI, PHD1	Q3 Y2	Q4 Y3		
Writing and submitting journal papers	PI, PHD1	Q3 Y3	Q4 Y4		
Mission 2: Macroscopic Insights into Ad Hoc Sensor Networks					
Action steps	Responsible	Time		Methodology	Deliverables, Implementation
		Start	End		
Literature/subject study workshop paper **PI-led conference paper**	PI, PHD1	Q1 Y1	Q4 Y1	Spatial Palm calculus Spatial PP theory Queueing theory Extreme value theory Ginibre PP New tessellations	1 workshop paper 2 conference papers 2 journal papers
Gathering ideas brainstorming	PI, PHD1	Q1 Y2	Q2 Y2		
Writing and publishing conference papers	PI, PHD1	Q3 Y2	Q4 Y3		
Writing and submitting journal papers	PI, PHD1	Q3 Y3	Q4 Y4		

the PI has been teaching introductory PP theory and Palm calculus in a Ph.D. course (course code: IK3506) since 2012 where the textbook written by Jean-Yves Le Boudec [9] is used. These subjects are **very rarely taught in engineering schools** across Europe. This course will crucially help to train the doctoral student participating in this study to learn those mathematical subjects.

X. A Detailed Implementation Plan of the Study

This study is due to be commenced in 2016 for four years involving the PI (committing 20% of total working time) who will devote himself not only to supervising project members and managing various aspects of the project but also to conducting research in separate as well as collaborative manners. There will be one Ph.D student who will contribute 80% of his/her time to the project for four years while spending 20% of his/her time in teaching duties at the department. A more detailed plan is summarized in Table I where **PI** and **PHD1** denote the PI and the Ph.D. student, respectively. While the the Ph.D. student will be accomplishing the two missions, the PI will also produce a couple of research outcomes which are primarily led and conducted by himself.

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[12] B. Liu and D. Towsley. A study on the coverage of large-scale sensor networks. In *Proc. IEEE International Conference on Mobile Ad-hoc and Sensor Systems (MASS)*, Oct. 2004.

[13] N. Miyoshi and T. Shirai. A cellular network model with Ginibre configured base stations. *Advances in Applied Probability*, 46(3):832–845, 2014.

[14] J. Møller. Random Johnson-Mehl tessellations. *Advances in Applied Probability*, 24(4):814–844, 1992.

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

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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	Jeong Woo Cho	20
2	PhD Student	PHD1	80

Salaries including social fees

	Role in the project	Name	Percent of salary	2016	2017	2018	2019	Total
1	Applicant	Jeong Woo Cho	20	142,000	146,000	149,000	153,000	590,000
2	PhD Student	PHD1	80	435,000	457,000	480,000	504,000	1,876,000
	Total			577,000	603,000	629,000	657,000	2,466,000

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	Offices	75,000	78,000	81,000	85,000	319,000
	Total	75,000	78,000	81,000	85,000	319,000

Running Costs

	Running Cost	Description	2016	2017	2018	2019	Total
1	Travel Costs	Conferences and workshops: twice/year	36,000	36,000	36,000	36,000	144,000
2	Publication Costs	Journals and magazines: once/year	14,000	14,000	14,000	14,000	56,000
3	Computer Costs	Desktop, laptop computers, and tablets	15,000	0	0	0	15,000
	Total		65,000	50,000	50,000	50,000	215,000

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	577,000	603,000	629,000	657,000	2,466,000		2,466,000
Running costs	65,000	50,000	50,000	50,000	215,000		215,000
Depreciation costs					0		0
Premises	75,000	78,000	81,000	85,000	319,000		319,000
Subtotal	717,000	731,000	760,000	792,000	3,000,000	0	3,000,000
Indirect costs	290,000	303,000	316,000	330,000	1,239,000		1,239,000
Total project cost	1,007,000	1,034,000	1,076,000	1,122,000	4,239,000	0	4,239,000

Explanation of the proposed budget

Briefly justify each proposed cost in the stated budget.

Explanation of the proposed budget*

The best part of the budget consists of the salary costs of the applicant committing 20% of his time, and a Ph.D. student contributing 80% of his/her time to the project while spending 20% of his/her time in teaching duties in the department. Other costs are: (i) the travel costs for conferences and workshops and (ii) the publications costs for journals and magazines.

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

Curriculum Vitae

Jeong Woo Cho

Department of Communication Systems (COS)
School of Information and Communication Technology (ICT)
KTH Royal Institute of Technology, Sweden
Homepage: http://people.kth.se/~jwcho/
Date of Birth: September 20th, 1978

Brief Biography

Jeong Woo Cho received his B.S., M.S., and Ph.D. degrees in Electrical Engineering and Computer Science from KAIST, Daejeon, South Korea, in 2000, 2002, and 2005, respectively. From September 2005 to July 2007, he was with the Telecommunication R&D Center, Samsung Electronics, South Korea, as a Senior Engineer. From August 2007 to August 2010, he held postdoc positions in the School of Computer and Communication Sciences, École Polytechnique Fédérale de Lausanne (EPFL), Switzerland, and at the Centre for Quantifiable Quality of Service in Communication Systems, Norwegian University of Science and Technology (NTNU), Trondheim, Norway. He is now an assistant professor in the School of Information and Communication Technology at KTH Royal Institute of Technology, Stockholm, Sweden. His current research interests include performance evaluation in various networks such as peer-to-peer network, wireless local area network, and delay-tolerant network.

1. Higher Education (KAIST is ranked 26th in 2014-2015 Times Higher's Engineering & Technology Ranking)

02/2002 — ***M.S.*** from School of Electrical Engineering and Computer Science
Korea Advanced Institute of Science and Techchnology (KAIST), South Korea
Thesis: **Dynamic Buffer Management Based on Rate Estimation in IP Networks**
Supervisor: Prof. Dong-Ho Cho

02/2000 — ***B.S.*** from School of Electrical Engineering and Computer Science
Korea Advanced Institute of Science and Techchnology (KAIST), South Korea

2. Doctoral Degree (KAIST is ranked 26th in 2014-2015 Times Higher's Engineering & Technology Ranking)

08/2005 — ***Ph.D.*** from School of Electrical Engineering and Computer Science ***(3.5 years)***
Korea Advanced Institute of Science and Techchnology (KAIST), South Korea
Thesis: **A Control-Theoretic Approach to Flow Control in Communication Networks**
Supervisor: Prof. Song Chong (Currently, an associate editor of IEEE/ACM Trans. Netw.)

3. Postdoctoral positions

08/2008-08/2010 — ***Postdoctoral Research Associate (Postdoc)***
Centre for Quantifiable Quality of Service in Communication Systems (Q2S)
Norwegian University of Science and Technology (NTNU), Norway
Supervisor: **Prof. Yuming Jiang**

08/2007-07/2008 — ***Senior Researcher (Postdoc)***
Computer Communications and Applications Laboratory
School of Computer and Communication Sciences
École Polytechnique Fédérale de Lausanne (EPFL), Switzerland
Supervisor: **Prof. Jean-Yves Le Boudec**

4. Docent Qualification

None

5. Current position

Since 09/2011 — ***Tenure-Track Assistant Professor*** **("Biträdande Universitetslektor" in Swedish)**
Department of Communication Systems
School of Information and Communication Technology (Headed by Jens Zander)
KTH Royal Institute of Technology (KTH), Sweden

6. Previous Positions

04/2015-05/2015 ***Visiting Researcher*** (Hosted by **François Baccelli**)
University of Texas at Austin (UT Austin), USA
The host ***pioneered*** and is now ***leading*** spatial PP approach. See Section IX.
Local & hotel expenses of the one-month stay were covered by UT Austin.

08/2010-08/2011 ***Associate Research Professor***
Department of Electrical Engineering, KAIST, South Korea

09/2005-07/2007 ***Senior Engineer***
Wireless Standards and Research Laboratory
Samsung Electronics, South Korea
Worked on 3GPP LTE standardization and attended its international meetings.

7. Interruption in Research

09/2005-07/2007 His work experience during two years from 2005 to 2007 at Samsung Electronics was an alternative to **obligatory conscription** in South Korea. He was not allowed to conduct research in this period.

8. Supervision

Since 01/2014 Co-supervising Voravit Tanyingyong who is expected to receive his Ph.D. in 2017.

Long-term Research Theme: Performance evaluation of wired/wireless networks.
Areas: IEEE 802.11 Wireless Local Area Network (WLAN), delay-tolerant network, peer-to-peer network
Methodologies: control theory, game theory, mean field theory, optimization theory, point process theory

Academic Services

TPC ICCCN 2012-2014, IEEE VTC 2014 Spring

Reviewer IEEE/ACM Trans. on Networking, IEEE Trans. on Communications, IEEE Trans. on Wireless Communications, IEEE Trans. on Parallel and Distributed Systems, Elsevier Computer Networks, Elsevier Computer Communications, IEEE Communications Letters, Journal of Communications and Networks, Annals of Telecommunications, Springer Wireless Networks, Springer Telecommunication Systems, ACM Mobicom, IEEE Infocom, IEEE ICC, IEEE Globecom, ...

Teaching at KTH

- "Performance Evaluation for Network Engineering" (KTH Course Code: IK3506) – A doctoral course which covers an introduction to **PP theory** and **Palm calculus** where the textbook written by Jean-Yves Le Boudec [9] is used. To the best of PI's knowledge, these subjects are **not taught in any engineering school in Europe** except at KTH and EPFL. Note also that this course has been hugely successful in spite of its highly theoretical nature. For example, one student commented:
  "*Overall a good course, with really useful course material. I think that taking it a year or so back would have saved me some pain in my research.*"
- "Advanced Internetworking II" (KTH Course Code: IK2217) – A master-level course covering advanced topics in networking, *e.g.*, Wi-Fi medium access and max-min & proportional fairness

Major Collaboration

- **Jean-Yves Le Boudec** is an IEEE Fellow and one of the most distinguished researchers in the field (Google Scholar citation counts as of March 2015: 20521). He has **pioneered** new research methodologies in the field such as **mean field theory**, **network calculus**, and **Palm calculus**. He earned 2008 IEEE Communications Society William R. Bennett Prize in the Field of Communications Networking (for *refined* theoretical foundation of max-min fairness), and best paper awards from IEEE Infocom 2005 (for Palm calculus approach to mobility models), and ACM Sigmetrics 2009 (for mean field analysis of delay tolerant networks). He served as an associate editor of IEEE/ACM Trans. Networking and many other journals.
- **Yung Yi** has been actively publishing a number of papers in **top-tier venues** including IEEE/ACM Trans. Networking, IEEE Trans. Information Theory, and ACM Sigmetrics. He received Ph.D. from University of Texas at Austin in 2006 and was a postdoc at Princeton University, from 2006 to 2008, under supervision of Mung Chiang, who is the most eminent researcher in optimization theory approach to communication networks. He is now an associate editor of IEEE/ACM Trans. Networking.
- He also worked with (i) Yuming Jiang at NTNU, Norway, who developed **stochastic network calculus**, and (ii) Song Chong at KAIST, South Korea, who is now an associate editor of IEEE/ACM Trans. Networking and other journals. He briefly worked with Jeonghoon Mo at Yonsei University, South Korea, who authored "Fair end-to-end window-based congestion control" (DOI: 10.1109/90.879343) which is one of the most cited paper in theoretical field of networking.

Publication list

Publication Over The Last 8 Years (Since 2007)

Representative publications *after* his Ph.D. (citation counts: Google Scholar)

[PI1] ⁎**Jeong-woo Cho**, Yuming Jiang, “Fundamentals of the Backoff Process in 802.11: Dichotomy of the Aggregation”, ***IEEE Transactions on Information Theory***, 61(4):1687-1701, Apr. 2015. DOI: 10.1109/TIT.2015.2404795. [Number of citations: 14]
: By leveraging **PP theory**, this work establishes the power-law principle of the delay distribution in Wi-Fi networks, which has been a longstanding tantalizing problem. This principle was **conjectured by many researchers** in networking community (See also Section IX).
: In terms of idea generation, analysis, simulation and writing, the PI contributed at least **95%** to the paper. The second author only proofread the paper a couple of times.

[PI2] ⁎**Jeong-woo Cho**, Jean-Yves Le Boudec, Yuming Jiang, “On the Asymptotic Validity of the Decoupling Assumption for Analyzing 802.11 MAC Protocol”, ***IEEE Transactions on Information Theory***, 58(11):6879-6893, Nov. 2012. DOI: 10.1109/TIT.2012.2208582. [Number of citations: 20]
: By using **mean field theory**, this work dare to **question the validity of so-called Bianchi’s formula** which is *de facto* standard tool for analyzing Wi-Fi (802.11) medium access control protocol (See also Section IX).
: The original idea was provided by the second author, which the PI developed for about two years (2007-2009). The PI contributed about **80%** to the paper.

[PI3] ⁎**Jeong-woo Cho**, Yung Yi, “On the Payoff Mechanisms in Peer-Assisted Services with Multiple Content Providers: Rationality and Fairness”, ***IEEE/ACM Transactions on Networking***, 22(3):731-744, June 2014. DOI: 10.1109/TNET.2013.2259637. [Number of citations: 6]
: The PI ventured into **coalition game theory** which he studied by himself. To fairly divide the total revenue among multiple content providers belonging to the same coalition, he proved a generalized version of *Aumann-Shapley price*, which is the **key formula in the coalition game theory under the mean field regime** (many-player regime).
: While the best part of the work including idea generation was done by the PI, the second author also made significant editorial efforts. The PI contributed **85%** to the paper.

[PI4] ⁎Jaeseong Jeong, Yung Yi, **Jeong-woo Cho**, Do Young Eun, Song Chong, “Energy-efficient Wi-Fi Sensing Policy under Generalized Mobility Patterns with Aging”, under revision for ***IEEE/ACM Transactions on Networking***, Dec. 2014. (an earlier version was published in ***IEEE Infocom 2013*** where the acceptance rate was **17%**. DOI: 10.1109/INFCOM.2013.6567037). [Number of citations: 5]
: The PI helped the first author to formulate the **functional optimization** problem to detect Wi-Fi access points energy-efficiently where the PI also applied one of key concepts in **Palm calculus**.
: This work was mostly done by the first three authors. The PI contributed about **20-25%**. The PI was originally the second author in earlier versions of the work but decided to delegate it to Yung Yi who was the supervisor of the first author, Jaeseong Jeong.

[PI5] ⁎**Jeong-woo Cho**, Jeonghoon Mo, Song Chong, “Joint Network-wide Opportunistic Scheduling and Power Control in Multi-cell Networks”, ***IEEE Transactions on Wireless Communications***, 8(3) 1520-1531, Mar. 2009. DOI: 10.1109/TWC.2009.080498. (a preliminary version was published in ***IEEE WoWMoM 2007*** where the acceptance rate was **10%**). [Number of citations: 44]
: This work investigates network-wide coordination of scheduling and power control (equivalent to interference coordination) to achieve α-proportional fairness by making use of **optimization theory**.
: The PI’s Ph.D. supervisor (the third author) **did not contribute** to this paper at all, not even a single proofreading. The contribution of PI is about **85%**.

[PI6] **Jeong-woo Cho**, Yung Yi, “On the Shapley-like Payoff Mechanisms in Peer-Assisted Services with Multiple Content Providers”, ***Lecture Notes of the Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering (LNICST)***, 75:397-412, 2012. DOI: 10.1007/978-3-642-30373-9_28. (a preliminary version was published in ***GameNets 2011***).
: This work is PI’s **first adventure** to coalition game theory where only Shapley payoff mechanisms are considered as compared with its extended version, *i.e.*, Paper [PI3].
: The second author made almost minor contributions. The PI contributed **90%** to the paper.

Representative publications *during* his Ph.D. (citation counts: Google Scholar)

[PI7] **Jeong-woo Cho**, Song Chong, "Utility Max-Min Flow Control Using Slope-Restricted Utility Functions", ***IEEE Transactions on Communications***, 55(5):963-972, May 2007. DOI: 10.1109/TCOMM.2007.896066. [Number of citations: 39]
: This work was the greatest achievement of PI's Ph.D. research where he made use of **nonlinear control theory** to prove the stability of **delay differential equations**, which are used to model the distributed **utility max-min** flow control algorithms. Stability analysis of utility max-min fairness was one of the most challenging problems at the time in networking community.
: The original raw idea was provided by the PI's supervisor. However, the PI tackled the problem alone and was not aided by his supervisor who was on sabbatical at the time. The contribution of PI is about **90%**.

[PI8] Hyang-Won Lee, **Jeong-woo Cho**, Song Chong, "Distributed Max-Min Flow Control for Multi-rate Overlay Multicast", ***Computer Networks***, 54(11):1727-1738, Aug. 2010. DOI: 10.1016/j.comnet.2010.02.004. [Number of citations: 17]
: This work is an extension of PI's Ph.D. work to multi-rate multicast flow control algorithms.
: The PI contributed about 10% to this paper.

Other publications

[PI9] Hyojung Lee, Hyeryng Jang, Yung Yi, **Jeong-woo Cho**, "On the Interaction Between Content-oriented Traffic Scheduling and Revenue Sharing Among Providers", ***2nd IEEE International Workshop on Smart Data Pricing (SDP 2013) held in conjunction with IEEE Infocom 2013***, Turin, Italy, Apr. 2013.

[PI10] Jaeseong Jeong, Yung Yi, **Jeong-woo Cho**, Do Young Eun, Song Chong, "Wi-Fi Sensing: Should Mobiles Sleep Longer As They Age?", ***IEEE Infocom 2013***, Turin, Italy, Apr. 2013.

[PI11] Hyojung Lee, Hyeryng Jang, **Jeong-woo Cho**, Yung Yi, "On the Stability of ISPs' Coalition Structure: Shapley Value Based Revenue Sharing", ***46th Conference on Information Sciences and Systems (CISS)***, Princeton University, New Jersey, Mar. 2012.

[PI12] **Jeong-woo Cho**, Yung Yi, "On the Shapley-like Payoff Mechanisms in Peer-Assisted Services with Multiple Content Providers", ***GameNets 2011***, Shanghai, China, Apr. 2011.

[PI13] **Jeong-woo Cho**, Jean-Yves Le Boudec, Yuming Jiang, "On the Validity of the Fixed Point Equation and Decoupling Assumption for Analyzing the 802.11 MAC Protocol", ***ACM SIGMETRICS Performance Evaluation Review***, 38(2):36-38, Sep. 2010.

[PI14] **Jeong-woo Cho**, Jean-Yves Le Boudec, Yuming Jiang, "On the Validity of the Fixed Point Equation and Decoupling Assumption for Analyzing the 802.11 MAC Protocol", ***ACM SIGMETRICS MAMA 2010***, New York City, New York, June 2010.

[PI15] **Jeong-woo Cho**, Yuming Jiang, "Basic Theorems on the Backoff Process in 802.11", ***ACM SIGMETRICS Performance Evaluation Review***, 37(2):18-20, Sep. 2009.

[PI16] **Jeong-woo Cho**, Yuming Jiang, "Basic Theorems on the Backoff Process in 802.11", ***ACM SIGMETRICS MAMA 2009***, Seattle, Washington, June 2009.

[PI17] Yuehong Gao, Xin Zhang, Yuming Jiang, **Jeong-woo Cho**, "System Spectral Efficiency and Stability of 3G Networks: A Comparative Study", ***IEEE ICC 2009***, Dresden, Germany, June 2009.

[PI18] **Jeong-woo Cho**, Jeonghoon Mo and Song Chong, "Joint Network-wide Opportunistic Scheduling and Power Control in Multi-cell Network", ***IEEE WoWMoM 2007***, Helsinki, Finland, June 2007. (acceptance rate of an extended paper: 10.1%=15/148)

Awards

[W1] Student Travel Grants for IEEE Globecom 2004 (Competitive rate: 24.4%=11/45), IEEE Communications Society, Dec. 2004.

[W2] Student Travel Grants for IEEE Globecom 2005 (Competitive rate: 41.7%=10/24), IEEE Communications Society, Dec. 2005.

Some Important Remarks

- IEEE/ACM Transactions on Networking and IEEE Transactions on Information Theory are ***arguably the two most prestigious journals*** in the field of networking. The PI has three of them (plus one under revision) as **the first author in the last 2.5 years**.
- It is **very rare** to receive a Ph.D. degree in 3.5 years at KAIST, South Korea. The average duration of Ph.D. studies was around 5-5.5 years. Also, the PI conducted the research which resulted in Paper [PI7] **almost alone** because his supervisor was on a sabbatical leave (Aug. 2004-Aug. 2005). In retrospect, however, to be fair to his supervisor, the PI is rather thankful that his supervisor fostered **independence** in him.

CV

Name: Jeong Woo Cho	**Doctorial degree:** 2005-08-19
Birthdate: 19780920	**Academic title:** Annan
Gender: Male	**Employer:** Kungliga Tekniska högskolan

Research education

Dissertation title (swe)

A Control-Theoretic Approach to Flow Control in Communication Networks

Dissertation title (en)

A Control-Theoretic Approach to Flow Control in Communication Networks

Organisation	Unit	Supervisor
Korea Advanced Institute of Science and Technology, Korea , South Not Sweden - Higher Education institutes	School of Electrical Engineering and Computer Science	Song Chong

Subject doctors degree	ISSN/ISBN-number	Date doctoral exam
20203. Kommunikationssystem		2005-08-19

Publications

Name: Jeong Woo Cho	**Doctorial degree:** 2005-08-19
Birthdate: 19780920	**Academic title:** Annan
Gender: Male	**Employer:** Kungliga Tekniska högskolan

Cho, Jeong Woo 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.