Report from Dagstuhl Seminar 17271

Foundations of Wireless Networking

Edited by

Christina Fragouli[1], Magnús M. Halldórsson[2], Kyle Jamieson[3], and Bhaskar Krishnamachari[4]

1 **University of California at Los Angeles, US,** christina.fragouli@ucla.edu
2 **Reykjavik University, IS,** mmh@ru.is
3 **Princeton University, US & University College London, GB,** kylej@cs.princeton.edu
4 **USC - Los Angeles, US,** bkrishna@usc.edu

Abstract

This report documents the talks and discussions of Dagstuhl Seminar 17271 "Foundations of Wireless Networking". The presented talks represent a wide spectrum of work on wireless networks.

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1 Executive Summary

Christina Fragouli
Magnús M. Halldórsson
Kyle Jamieson
Bhaskar Krishnamachari

Wireless communication has grown by leaps and bounds in recent decades, with huge social and societal impact. This is nowhere near saturation, especially with the coming Internet-of-Things on the horizon.

Underlying this technology are fundamental questions: how to efficiently configure and adapt communication links, organize access to the medium, overcome interference, and disseminate information. Unfortunately, the wireless medium is tricky, and the modeling of signal propagation and interference has proved to be highly involved, with additional challenges introduced by issues such as mobility, energy limitations, and device heterogeneity. New technologies such as cooperative MIMO, directional antennas, interference alignment, network coding, energy harvesting and motion control add another layer of complexity, and are yet to be well-understood. Deriving good algorithms and protocols is therefore a non-trivial task.

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Communities

Different schools of thought have arisen to tackle these fundamental questions. These come from different backgrounds, involving different types of mathematical tools and different approaches and outlooks. It is not just a theory vs. practice split, but also splits within the theory and the practice camps. In addition to the more established information theory, there has been quite some work on network control theory, and also a budding algorithmic theory; on top of physical-layer hardware experimentation, we see also networking systems research and simulation studies.

We identified the following communities, which are not all exclusive:

Information Theory Characterized by an interest in fundamental information-theoretic capacity bounds; novel communication paradigms such as MIMO, network coding, interference cancellation, interference alignment; estimation and detection under known stochastic models of noise.
Prime publication venues: IEEE Trans. on Information Theory; IEEE International Symposium on Information Theory (ISIT).

Algorithm Theory Characterized by a focus on algorithms, their complexity and effectiveness, with emphasis on rigorous proofs and typically worst-case analysis.
Prime publication venues: PODC, DISC, STOC, SODA, ICALP (Track C)

Experimental Mobile and Wireless Systems Characterized by the design, implementation, and evaluation of practical wireless systems in real testbeds and real-world applications that both both evaluate the efficacy of previously-known techniques and their combinations "in the wild" and add design insight by developing novel heuristic algorithms and architectures that are shown to perform well in practice.
Prime publication venues: MobiCom, MobiHoc, SIGCOMM, NSDI, SenSys, IPSN, BuildSys, MobiSys.

Wireless Network Control and Optimization Theory Characterized by formulation of various problems in wireless networks (typically focusing on medium access, network routing and flow rate control) as continuous control and optimization problems from both deterministic and stochastic perspectives; network utility optimization via primal-dual decomposition, game theory, stochastic decision theory, stochastic multi-armed bandits.
Prime publication venues: Infocom, SIGMETRICS, WiOpt, CDC, IEEE Trans. on Networking, IEEE Transactions on Automatic Control.

Physical Layer and Hardware Design Characterized by the design, implementation, and evaluation of new hardware, signal processing techniques. The theoretical members of this community have a lot of overlap with information theory, while the more experimental members of this community have a lot of overlap with the experimental wireless and mobile systems community in terms of the problems they consider and their solution approaches.
Prime publication venues: IEEE Trans. on Wireless, IEEE Trans. on Comms., IEEE Globecom, IEEE Vehicular Technology Conf.

Goals of the Seminar

The goal of this Dagstuhl seminar is to bring together top researchers from the different wireless research communities to review and discuss models and methods in order to obtain a better understanding of the capabilities and limitations of modern wireless networks, and to come up with more realistic models and new algorithm and protocol design approaches for future wireless networks that may then be investigated in joint research projects.

An important part of the workshop is to actively promote a dialog between different communities. As a result, we seek researchers that are by nature open to different perspectives and have enough self-confidence to welcome research of a different nature. The objective was for each participant to consciously reflect on the implicit values, identity, shared understandings and skill set that people in his/her community expect, and to articulate these issues to others in order to identify and appreciate commonalities and differences, and the potential gains from forming new bridges.

Seminar Operation

The seminar had varied forms of activities during its operation. As people came from different communities, a major objective was to get to know each other.

"Speak-and-spark" presentations All the participants gave a brief, 5-10 minute pitch talk on a problem that they have been (or would to be) working on. Most of these were given on the first day, which provided a way of introducing one another, as well as a way to spark discussions that could be continued in private, in small groups, or in plenum.

Survey presentations Seven senior researchers were asked to give a one-hour survey talk on a topic of current interest. These were spread over the days excluding the first.

Breakout sessions Several topical issues were identified as particularly suitable for group discussions. The participants voted on the topics of their interest, after which three were selected. The groups were chosen so as to feature representatives from the different communities. Two such rounds of breakout sessions were organized on Tuesday. The discussions were summarized by the group leaders (often with the help of the scribes) for the whole audience on Wednesday morning, followed by discussions.

"Important paper" pitches The participants were encouraged to identify research paper(s) that open "new" research areas and/or pose questions in their community. This was also a means to articulating what researchers in that subfield found essential or influential. These were the presented in 5-10 minutes, followed by open questions.

Plenary discussions Part of the last day's morning was allocated to general discussions around the themes posed during the seminar, with the aim of identifying future problem directions and research areas.

Abstracts and summaries of these talks and discussions are given in the following sections.

2 Table of Contents

3 Survey Talks

3.1 Breaking some communications paradigms: Spectrally efficient non-orthogonal signals concepts and practical implementation

Izzat Darwazeh (University College London, GB)

Joint work of Izzat Darwazeh, Safa Issam, Ioannis Kanaras, Ryan Grammenos, Tongyang Xu, John Mitchell, Spiros Mikroulis, Zhaohui Li, Waseem Ozan, Hedaia Ghannam, Kyle Jamieson
Main reference Tongyang Xu, Izzat Darwazeh: "Transmission Experiment of Bandwidth Compressed Carrier Aggregation in a Realistic Fading Channel", IEEE Trans. Vehicular Technology, Vol. 66(5), pp. 4087–4097, 2017.
URL http://dx.doi.org/10.1109/TVT.2016.2607523

The talk details work done at University College London (UCL) and elsewhere on the general concepts, fundamentals and experimental validations of bandwidth compressed multicarrier waveforms for future wireless and wired systems. The proposed waveforms are derived from an existing non-orthogonal multicarrier concept termed spectrally efficient frequency division multiplexing (SEFDM) where sub-carriers are non-orthogonally packed at frequencies below the symbol rate. This improves the spectral efficiency at the cost of self-created inter carrier interference (ICI). In this presentation experiments are reported and testing is carried out in three scenarios including long term evolution (LTE)-like wireless link; millimeter wave radio-over-fiber (RoF) link and optical fiber links. In the first scenario, for a given 25 MHz bandwidth, the SEFDM testbed can provide 70 Mbit/s gross data rate while only 50 Mbit/s can be achieved for an OFDM system occupying the same bandwidth. For the millimeter wave experiment, occupying a 1.125 GHz bandwidth, the gross bit rate for OFDM is 2.25 Gbit/s and with 40% bandwidth compression, 3.75 Gbit/s can be achieved for SEFDM. Two experimental optical fiber links are described in this work; a 10 Gbit/s direct detection optical SEFDM system and a 24 Gbit/s coherent detection SEFDM system. The LTE-like signals and millimeter wave technologies are well suited to provide last mile communications to end users as both can support mobility in wireless environments. The lightwave signals delivered by optical fibers would offer higher data rates and support long-haul communications. The reported techniques, used individually or combined, would be of interest to future wireless system designers, where bandwidth saving is of importance, such as in 5G networks, aiming to provide high capacity and high mobility, simultaneously while saving spectrum. New signals, derived from SEFDM are discussed and new applications, including x-DSL like scenarios are outlined.

3.2 Developing Robust Wireless Network Algorithms (from a TCS perspective)

Fabian Daniel Kuhn (Universität Freiburg, DE)

Over the last 30 years, we have seen an intensive effort to develop distributed algorithms and abstract models to deal with the characteristic properties of wireless communication. The models range from simple graph-based characterizations of interference to more accurate physical models such as the so-called signal-to-noise-and-interference (SINR) model.

As different as the typically considered models may be, most of them have one thing in common. Whether a node can successfully receive (and decode) a message is determined using some fixed, deterministic rule that depends on the structure of the network and some additional model parameters.

While in classical wired networks, assuming reliable communication might be a reasonable abstraction, this seems much more problematic in a wireless network setting. The propagation of a wireless signal depends on many diverse environmental factors and it does not seem to be realistic to explicitly model all of these factors or to exactly measure the properties of the wireless communication channels. In addition, the environmental factors might change over time and there can also be additional independent sources of signal interference that cannot be predicted or controlled by the network. Further, wireless devices might also be mobile so that we not only have unreliable communication channels, but potentially even almost arbitrary dynamically changing network topologies. Because the classic abstract wireless communication models do not capture such unpredictable behavior, many existing radio network algorithms might only work in the idealized formal setting for which they were developed.

In my talk, I describe ways to develop more robust wireless network algorithms. I will in particular show that complicated, unstable, and unreliable behavior of wireless communication can be modeled by adding a non-deterministic component to existing radio network models. As a result, any behavior which is too complex or impossible to predict is determined by an adversary. Clearly, such models lead to leá efficient algorithms. However, they also lead to more robust algorithms which tend to work under a much wider set of underlying assumptions. Very often, such models also lead to much simpler algorithms. I will discuss several existing results and I will sketch some general ideas and possible directions for dealing with adversarial uncertainty and more generally dynamic wireless networks.

3.3 PHY Layer Design For Extreme Resource Sharing

Konstantinos Nikitopoulos (University of Surrey, GB)

Joint work of Konstantinos Nikitopoulos, Georgios Georgis, Christopher Husmann, F. Mehran, C. Jaywardena, Kyle Jamieson, H. Jafarkhani, and R. Tafazolli

Future local area wireless communication systems shall be able to support very high peak user and network rates as well as very large numbers of connected devices, while keeping the latency requirements at very low levels. These needs have triggered a paradigm shift from orthogonal to non-orthogonal signal transmissions that enable extreme sharing of the available resources, including frequency and time. Such schemes include multi-antenna (MIMO) deployments for aggressive spatial multiplexing, as well as non-orthogonal multiple access schemes. In practice, to deliver the theoretical gains of such large non-orthogonal schemes, the mutually interfering information streams must be efficiently demultiplexed. However, the processing requirements of ML detection increase exponentially with the number of mutually interfering information streams, exceeding the processing capabilities of traditional processors. In this context we show that FlexCore; the first method to massively parallelize the ML detection problem in a nearly- independent manner, can overcome the current processing speed barriers. In addition, we show that new PHY approaches like out newly proposed Space-Time Super-Modulation can be efficiently used in the context of machine-type communications to enable joint medium access and rateless data transmission while reducing or even eliminating the need for transmitting preamble sequences.

3.4 Cooperation in Wireless Networks – An Information-Theoretic Viewpoint

Michelle Effros (CalTech – Pasadena, US)

We consider the cost and benefit of cooperation in wireless communication networks. Here, cost is measured by teh capacity added to the network to enable the cooperation, while benefit is measured by the amount that the network capacity increases due to the optimal cooperative strategy enabled by that addition. For wireline networks, whether the benefit can exceed the cost remains an open problem. For wireless networks, we show that benefit can exceed any polynomial function of the cost, that the cost-benefit curve exhibits an infinite slope at the limit of small cost, and that in some cases even an infinitesimal cost leads to a finite benefit resulting in a discontinuity in the cost-benefit curve.

3.5 Some Topics and Problems in Wireless Networking

Muriel Médard (MIT – Cambridge, US)

We consider the interplay between information theory and practical networking in terms of a series of questions:

- What should the physical layer do?
- How do we deal with interference?
- How about cooperation?
- What about delay?
- What are the trade-offs?
- What about heterogeneity?
- Where does storage fit in?

We argue that equivalence theory points towards separating physical layer coding from the network, but that, in other respects, coding and networking are inextricably linked. In particular, while coding has generally been used to create a synthetic reliable pipe from lossy transmission media, it can be similarly used to synthesize different services, with varying delay and throughput trade-offs, over shared and often heterogeneous links, and over varied and distributed storage media, in a fluid approach.

3.6 Survey on “Economics in Wireless”

Vijay Subramanian (University of Michigan – Ann Arbor, US)

There are many topics where economics and game theory appear in wireless. The first and foremost is in investments and auctions of spectrum resources, which is a public resource in most countries that is auctioned to providers with defined property rights. Designing computationally efficient, social-welfare maximizing, truthfully spectrum auctions in which providers voluntarily participate is challenging. Resource allocation games and their impact on market design is a topic where one can use general equilibrium theory based analysis to understand competition and sharing in wireless systems. Micro-payments using real-time distributed markets and auctions can be used for pricing, incentives and sharing in wireless systems. Finally, interference prices and best-response dynamics from the service providers can be used for scheduling and resource allocation.

3.7 Some interesting optimization problem formulations

Michele Zorzi (University of Padova, IT)

In this talk, I will try to motivate the audience to understand some of the interesting and relevant stochastic optimization problems being addressed in the wireless networking area. This is in the spirit of trying to create a common understanding of each other's relevant research problems and possibly to stimulate cross-discipline collaboration or simply an appreciation of what others are doing. Towards this aim, I will present some problem formulations on which I have been working in the past few years, trying to describe how we approach problems, choose performance metrics, use tools and find solutions.

In particular, I will address the following areas: (i) derivation of an optimal transmission policy for an energy-harvesting device; (ii) derivation of an optimal transmission strategy for a secondary user in a cognitive radio scenario with ARQ and Interference Cancellation; (iii) study of optimal policies for wireless powered communication networks with doubly near-far effect; (iv) decentralized solutions for the multi-user MAC problem for energy-harvesting devices.

4 Summaries of "Speak-and-Spark" Talks

4.1 Massive MIMO and Compressed Sensing: a marriage made in 5G

Giuseppe Caire (TU Berlin, DE)

Massive MIMO channel estimation presents a number of problems ideally suited for compressed sensing. In 5 min I'd like to give an idea of why this happens and why compressed sensing can be very useful.

4.2 Simplicity and Robustness (or all about noisy beeping)

Seth Gilbert (National University of Singapore, SG)

Joint work of Seth Gilbert, Calvin Newport

We have been thinking about very simple forms of communication where entities can only communicate by beeping, such as either very simple sensors of biological networks. There are two basic questions we want to answer:

- Can we develop algorithms that are actually simple? (Or when we make the communication model simpler, do we inherently end up with more complicated algorithms?)
- Can we develop simple algorithms that are robust? (Especially in the context of biological systems, there is significant noise that can disrupt a computation; can we over come it?)

To answer these questions, we have developed simple and robust algorithms as well shown lower bounds delineating the boundary of what is feasible.

4.3 Spatial Outage Capacity: The Missing Link between Average and Worst-Case Performance?

Martin Haenggi (University of Notre Dame, US)

Joint work of Sanket Kalamkar and Martin Haenggi
Main reference S. S. Kalamkar and M. Haenggi, "The Spatial Outage Capacity in Wireless Networks", arXiv:1708.05870v1 [cs.IT], 2017.
URL https://arxiv.org/abs/1708.05870

This brief presentation addresses a fundamental problem in wireless networks: what is the maximum density of reliable links that the network can support? This metric is called the spatial outage capacity (SOC). Reliability is captured using a constraint on the outage probability of a link, and the reliable link density is maximized over the node density λ and the transmit probability p. Surprisingly, this question has not been addressed before. Our analysis for Poisson networks with ALOHA shows that, surprisingly, that (unless the target reliability is small) the SOC is achieved by setting $p = 1$, i.e., by having all transmitters always active. This is counter-intuitive since one would think that in order to achieve high reliability, interference needs to be managed by allowing transmitters to be active only a fraction of time. In the high reliability regime, as the target outage probability goes to zero, we have obtained simple closed-form results on the SOC. It only depends on the rate-reliability ratio and the path loss exponent.

4.4 Intelligence and Network

Longbo Huang (Tsinghua University – Beijing, CN)

In this talk, I will survey some recent results we have on learning-aided stochastic network optimization. I will also introduce our recent effort on understanding the role of pricing and subsidies in the sharing economy and fast-convergence optimization algorithm design.

4.5 Fault-Tolerant Online Packet Scheduling on (Wireless) Channel(s)

Tomasz Jurdzinski (University of Wroclaw, PL)

Joint work of Pawel Garncarek, Tomasz Jurdzinski, Dariusz R. Kowalski, Krzysztof Lorys
Main reference Pawel Garncarek, Tomasz Jurdzinski, Krzysztof Lorys: "Fault-Tolerant Online Packet Scheduling on Parallel Channels", in Proc. of the 2017 IEEE International Parallel and Distributed Processing Symposium, IPDPS 2017, Orlando, FL, USA, May 29 - June 2, 2017, pp. 347–356, IEEE Computer Society, 2017.
URL http://dx.doi.org/10.1109/IPDPS.2017.105

This pitch talk discusses the model of online packet scheduling on (wireless) channel under adversarial errors [1] and its generalizations. An online algorithm is supposed to schedule dynamically arriving packets of various lengths, while transmissions of packets might be broken by an adversary. Focus on errors of transmission and various packets lengths reflect key features of contemporary wireless communication: high probability of errors on a communication channel and various requirements of services. In [3], an online algorithm for scheduling packets of arbitrary lengths is given, achieving optimal competitive throughput in $(1/3, 1/2]$. The model from [1] is generalized in [2] to the scenario with many parallel dependent channels. It is shown that the fact that errors have to appear simultaneously is beneficial for an online algorithm. Namely, an algorithm is designed which achieves the competitive throughput above $1/2$ for $p > 1$ channels, approaching $3/4$ with increasing number of channels.

References

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2 P. Garncarek, T. Jurdzinski, and K. Lorys. Fault-tolerant online packet scheduling on parallel channels. In *2017 IEEE International Parallel and Distributed Processing Symposium, IPDPS 2017, 2017*, pages 347–356, 2017.
3 Tomasz Jurdzinski, Dariusz R. Kowalski, and Krzysztof Lorys. *Online Packet Scheduling Under Adversarial Jamming*, pages 193–206. In *Approximation and Online Algorithms – 12th International Workshop, WAOA 2014*, Springer, pages 193–206, 2014.

4.6 Some Thoughts on Wireless Networking Research

Holger Karl (Universität Paderborn, DE)

1. NFV meets wireless multi-hop networks
   NFV has so far mostly been considered for fixed networks (core, mobile backhaul, mobile fronthaul networks, etc). Very little work has so far been invested in looking into the NFV concepts (and the algorithms that have emerged there) when applied to multi-hop networks. One possible application area might be acoustic sensor networks: microphones distributed in a network, non-trivial acoustic signal processing (e.g., speaker separation) at non-trivial data rates. The algorithmic challenge is to treat the placement (and possibly scaling) of individual function blocks in the network and the routing along interfering

paths as an integrated problem. It should result in many variations of this problem under plenty of different scenario assumptions.
See https://cs.uni-paderborn.de/cn/research/research-projects/active-projects/acoustic-sensor-networks/ for mode details

2. Control over wireless
Is there benefit by tighter integration between a wireless resource management system and a typical control application? Suppose we have a wireless cell, a controller which controls different sensors actuators over multiple wireless connections which have to share the resources in that link. The controller can send or request different amounts of data to each device under its control, obtaining more or less information or exerting more exact control. Links are assumed to undergo fading (independent? correlated? to be seen). In different situations of the controlled system, different actuators/sensors become urgent or irrelevant to be considered. Knowledge about this sits in the controller.
Goal is "best control performance" (e.g., minimize MSE) over a time-varying process. (Context: Throughput is usually not a problem; delay and error rates are much more relevant)
Question: how to best allocate wireless resources? How to design the interaction between controller and wireless resource management to that end?
See https://cs.uni-paderborn.de/cn/research/research-projects/active-projects/nicci/ for more details.
3. Slicing – blessing or curse?
In 5G, "Slicing" is considered to be a magic wand: Resources are allocated to individual (groups of) users (e.g., "vertical industries" like car, manufacturing, etc.). Inside a slice, a lot of freedom regarding choice of protocols, PHY, MAC, ... exists.
Question: What is the tradeoff between increasing flexibility and customizing to specific, better defined needs (over all-purpose protocols) vs. the reduced diversity / multiplexing gains by dividing resources in a fixed fashion?
(Implementation complexity might be another consideration; but likely hard to capture in a theoretic concept)
4. Other, more generic rants:
   - Why are we still bug-fixing broken protocols? CSMA/CA is not a promising tool for an AP-based scenario. There are reasons why cellular networks perform better, and their choice to do coordinated MAC is probably a big one of these reasons.
   - More generally, let's stop being in love with our models. Does the world really need more research on big mesh networks? Is there any single one

4.7 Routing in Hybrid Networks with Holes

Christina Kolb (Universität Paderborn, DE)

Joint work of Christina Kolb, Christian Scheideler

Think of you having a contract with a smartphone provider. This contract offers a fixed Internet vol-ume that is available for free, but that volume is rather small, so you want to use it as scarcely as possible. Fortunately, there are many other people nearby who are also interested in saving their Internet volume, including some of your friends. However, they are too far away from you to directly use WLAN communication, but in principle there would be a route via other people along which your messages can be sent using WLAN communication to communicate with your friends. But how to find such a route efficiently? It is well-known in the research community that doing that just via WLAN communication does not scale well, but some of the Internet volume could be used in order to exchange control information, such as the current geographic positions of your friends or the location and dimension of radio holes (i.e., areas with no participants). Hence, we can set up a so-called hybrid communication network between the participants in order to find routes for WLAN communication more efficiently, but how much more efficiently would that be?

In this talk, we present the model and goals of the setting above.

4.8 Enabling Extreme Resource Sharing in Future Wireless Communication Systems

Konstantinos Nikitopoulos (University of Surrey, GB)

There is a current paradigm shift from orthogonal to non-orthogonal signal transmissions that enables extreme sharing of the available resources, but it requires processing complexities far beyond the capabilities of traditional processors. In this context, massively parallel processing detection/decoding approaches are required to overcome the current processing speed barriers. In the same framework of extreme resource sharing, new PHY can be efficiently used to enable joint medium access and rateless data transmission while reducing or even eliminating the need for transmitting preamble sequences.

4.9 Towards a widely applicable SINR model for access sharing

Christian Scheideler (Universität Paderborn, DE)

I propose an SINR model in which Background noise is controlled by an adversary and present a preliminary solution for it.

4.10 Wake-up Transceivers, Convergecast, Beamforming, and Beat Frequencies

Christian Schindelhauer (Universität Freiburg, DE)

Joint work of Christian Schindelhauer, Thomas Janson, Amir Bannoura, Timo Kumberg
Main reference Timo Kumberg, Christian Schindelhauer, Leonhard M. Reindl: "Exploiting Concurrent Wake-Up Transmissions Using Beat Frequencies", Sensors, Vol. 17(8), p. 1717, 2017.
URL http://dx.doi.org/10.3390/s17081717

This pitch talks highlights three topics concerned with collaborative signal transmission and wake-up receivers.

In his PhD thesis Thomas Janson [1] has shown that a multi hop unicast with simultaneous sending can send a message within $O(\log \log n)$ hops and with energy $O(\log d)$, where single signal transmissions need linear time and energy with respect to the distance d. The open problem however is, whether such a beam can be widened for broadcast and how this affects time and energy.

Wireless Sensor Networks suffer from energy shortage and use duty cycling to reduce energy consumption and manage communication. Wake-up receivers overcome this problem. They always listens for own ID with some micro-Watts power consumption. Furthermore, every sensor node can send wake-up signals. However, they are short ranged and wake-up signals need additional time. In his PhD thesis Amir Bannoura [2] has shown several algorithms for broadcast and convergecast.

Combining these works Timo Kumberg et al. has considered the use of collaborative wake-up signals with different carrier frequencies such that the beat frequency produces the wake-up signal. Yet, it is not fully understood how such a construction scales for larger set of senders.

References

1 Thomas Janson *Energy-Efficient Collaborative Beamforming in Wireless Ad Hoc Networks*. PhD Thesis, University of Freiburg, 2015

2 Amir Bannoura, *Wake-Up Receivers Algorithms and Applications for Low Power Wireless Sensor Networks*. PhD Thesis, University of Freiburg, 2016

4.11 Distributed optimization for scheduling in wireless networks

Vijay Subramanian (University of Michigan – Ann Arbor, US)

Using the network utility maximization framework, we show how locally optimal scheduling and resource allocation can be performed using local updates, function approximation and consensus.

4.12 Fine-grain Time / Spectrum Sharing

Patrick Thiran (EPFL – Lausanne, CH)

Joint work of Julien Herzen, Albert Banchs, Vsevolod Shneer, Patrick Thiran

Main reference Julien Herzen, Albert Banchs, Vsevolod Shneer, Patrick Thiran: "CSMA/CA in Time and Frequency Domains", in Proc. of the 23rd IEEE International Conference on Network Protocols, ICNP 2015, San Francisco, CA, USA, November 10-13, 2015, pp. 256–266, IEEE Computer Society, 2015.

URL http://dx.doi.org/10.1109/ICNP.2015.16

It has recently been shown [see e.g. K. Tan et al, Proc. ACM SIGCOMM, 2010; S. Yun et al, Proc. ACM MobiCom, 2013] that flexible channelization, whereby wireless stations adapt their spectrum bands on a per-frame basis, is becoming feasible in practice. This offers the potential to strongly improve in the future the performance of MAC schemes, such as 802.11, which currently solve contention only in the time-domain. I briefly describe TF-CSMA/CA [J. Herzen et al, Proc. IEEE ICNP 2015], a first fully distributed algorithm for flexible channelization that schedules packets in time and frequency domains.

4.13 Wireless Link Capacity under Shadowing and Fading

Tigran Tonoyan (Reykjavik University, IS)

Joint work of Magnús M. Halldórsson, Tigran Tonoyan

We consider the following basic spatial reuse problem in wireless networks: Given a set of communication links, find a maximum subset of links that can successfully transmit in the same channel and time slot. The problem has many components, including the way signal attenuation and reception is modeled. We consider three aspects: geometric pathloss, shadowing (spatial) and temporal fading. Towards the goal of understanding the general behavior of networks, we adopt stochastic models describing the latter two phenomena: stochastic shadowing (e.g., Lognormal shadowing) and Rayleigh fading. We present algorithms computing solutions under stochastic shadowing and fading, with arbitrary placement of links. We further show that Rayleigh (temporal) fading affects the size of the solution only by a constant factor, while stochastic shadowing can give significantly better results than deterministic geometric pathloss alone. These results are obtained under some independence assumptions on the distributions. The main question to be answered is: how to model dependencies between distributions in general networks?

4.14 Information Theoretic Caching

Daniela Tuninetti (University of Illinois – Chicago, US)

I give a very short summary of some results in centralized coded caching.

4.15 Update or Wait: How to Get the Freshest and Most Accurate Data Through a Network

Elif Uysal-Biyikoglu (Middle East Technical University – Ankara, TR)

An ever increasing amount of data on today's networks is in the form of status updates. Often, the source that generates the data (e.g. sensor) and the remote application that uses the data are connected through a network with varying quality and delay.

We study how to optimally manage the freshness of information updates sent from the source of the data to the destination via a network with random delay. A proper metric for data freshness at the destination is the Age of Information, or simply age, which is defined as the amount of time that elapsed since the freshest received update received so far was generated at the source. A reasonable update policy is the zero-wait policy, i.e., the source node submits a fresh update once the previous update is delivered and the channel becomes free, which achieves the maximum throughput and the minimum delay. Surprisingly, this zero-wait policy, which is work-conserving (and optimal with respect to throughput and delay) does not always minimize the age. This counter-intuitive phenomenon motivates us to study how to optimally control information updates to keep the data fresh.

Next, we generalize the Age problem to consider a real-time sampling problem: Samples of a Wiener process are taken and forwarded to a remote estimator via a channel with random delay; the estimator forms a real-time estimate of the signal from causally received samples. The optimal sampling policy for minimizing the MMSE subject to a sampling-rate constraint is obtained exactly, which is determined by the signal, sampler, and channel in a simple form. Echoing the result of the Age problem, even in the absence of a restriction on sampling rate, there is a nonzero waiting time before taking the next sample. In fact, it is often optimal to sample below the maximum allowed sampling rate.

4.16 Storage Cost of Shared Memory Emulation

Zhiying Wang (University of California – Irvine, US)

Joint work of Viveck R. Cadambe, Nancy Lynch
Main reference Viveck R. Cadambe, Zhiying Wang, Nancy A. Lynch: "Information-Theoretic Lower Bounds on the Storage Cost of Shared Memory Emulation", in Proc. of the 2016 ACM Symposium on Principles of Distributed Computing, PODC 2016, Chicago, IL, USA, July 25-28, 2016, pp. 305–313, ACM, 2016.
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Main reference Zhiying Wang, Viveck Cadambe, "Multi-Version Coding – An Information Theoretic Perspective of Consistent Distributed Storage", arXiv:1506.00684v2 [cs.IT], 2015.
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Shared memory emulation are important algorithms that bridge the two communication models of asynchronous distributed systems: the shared-memory model, and the message-passing model. Previous literature has developed several shared memory emulation algorithms based on replication and erasure coding techniques. In this talk, we present information-theoretic lower bounds on the storage costs incurred by such algorithms. We show that the storage cost is at least twice that of the Singleton-type of bound; and for a restricted class of write protocols, the storage cost grows approximately linearly with the number of servers failures and the number of concurrent writes in an execution. An interesting observation is that, when the number of concurrent writes is large, replication based algorithms have asymptotically optimal storage cost.

4.17 PHY in Networks

Roger Wattenhofer (ETH Zürich, CH)

Joint work of Michael König, Roger Wattenhofer

I present some of our recent results regarding physical effects in networks, in particular (i) how to effectively capture attention using the capture effect, (ii) how to generate constructive interference using well-synchronized nodes, and (iii) how to share a medium between concurrent protocols without overhead.

References

1 Michael König, Roger Wattenhofer, Effectively Capturing Attention Using the Capture Effect. SenSys 2016: 70–82
2 Michael König, Roger Wattenhofer, Maintaining Constructive Interference Using Well-Synchronized Sensor Nodes. DCOSS 2016: 206–215
3 Michael König, Roger Wattenhofer, Sharing a Medium Between Concurrent Protocols Without Overhead Using the Capture Effect. EWSN 2016: 113–124

4.18 Problems in millimeter-wave communication: the difficult path from Gigabit links to Gigabit networks

Jörg Widmer (IMDEA Networks – Madrid, ES)

State-of-the-art wireless communication already operates close to Shannon capacity and one of the most promising options to further increase data rates is to increase the communication bandwidth. Very high bandwidth channels are only available in the extremely high frequency part of the radio spectrum, the millimeter wave band (mm-wave). Upcoming communication technologies, such as IEEE 802.11ad, are already starting to exploit this part of the radio spectrum to achieve data rates of several GBit/s. However, communication at such high frequencies also suffers from high attenuation and signal absorption, often restricting communication to line-of-sight (LOS) scenarios and requiring the use of highly directional antennas. This in turn requires a radical rethinking of wireless network design. On the one hand side, such channels experience little interference, allowing for a high degree of spatial reuse and potentially simpler MAC and interference management mechanisms. On the other hand, such an environment is extremely dynamic and channels may appear and disappear over very short time intervals, in particular for mobile devices. It is essential to take these characteristics into account to turn a collection of such very high speed but brittle links into an efficient, low latency, and reliable network. This talk will highlight some of the challenges of and possible approaches for mm-wave networking.

4.19 Wireless Networks: Dynamicity

Dongxiao Yu (Huazhong University of Science & Technology, CN)

Joint work of Dongxiao Yu, Yuexuan Wang, Tigran Tonoyan, Magnús M. Halldórsson
Main reference Dongxiao Yu, Yuexuan Wang, Tigran Tonoyan, Magnús M. Halldórsson: "Dynamic Adaptation in Wireless Networks Under Comprehensive Interference via Carrier Sense", in Proc. of the 2017 IEEE International Parallel and Distributed Processing Symposium, IPDPS 2017, Orlando, FL, USA, May 29 - June 2, 2017, pp. 337–346, IEEE Computer Society, 2017.
URL http://dx.doi.org/10.1109/IPDPS.2017.78

In this talk, we will introduce our recent efforts in distributed algorithm design in dynamic networks. Dynamic behavior is an essential part of wireless networking, due mobility, environmental changes or failures. We analyze a natural exponential backoff procedure to manage contention in a fading channel, in the presence of both node churn and link changes. We show that it attains a fast convergence, stabilizing contention from any state in logarithmic time. We use it to obtain optimal algorithm for Local Broadcast that even improves known results for the static case. The results illustrate the utility of carrier sensing, a stock feature of wireless nodes.

4.20 Passive Communication with Ambient Light

Marco Zuniga (TU Delft, NL)

Joint work of Domenico Giustiniano, Marco Zuniga, Qing Wang
Main reference Qing Wang, Marco Zuniga, Domenico Giustiniano: "Passive Communication with Ambient Light", in Proc. of the 12th International on Conference on emerging Networking EXperiments and Technologies, CoNEXT 2016, Irvine, California, USA, December 12-15, 2016, pp. 97–104, ACM, 2016.
URL http://dx.doi.org/10.1145/2999572.2999584

In this work, we propose a new communication system for illuminated areas, indoors and outdoors. Light sources in our environments –such as light bulbs or even the sun– are our signal emitters, but we do not modulate data at the light source. We instead propose that the environment itself modulates the ambient light signals: if mobile elements 'wear' patterns consisting of distinctive reflecting surfaces, single photodiode could decode the disturbed light signals to read passive information. Achieving this vision requires a deep understanding of a new type of communication channel. Many parameters can affect the performance of passive communication based on visible light: the size of reflective surfaces, the surrounding light intensity, the speed of mobile objects, the field-of-view of the receiver, to name a few. In this work, we present our vision for a passive communication channel with visible light.

5 Discussion groups

5.1 Discussion Group: Coding for New Channels

Michelle Effros (CalTech – Pasadena, US), Tomasz Jurdzinski (University of Wroclaw, PL), Konstantinos Nikitopoulos (University of Surrey, GB), Patrick Thiran (EPFL – Lausanne, CH), Jörg Widmer (IMDEA Networks – Madrid, ES), and Marco Antonio Zúñiga Zamalloa (TU Delft, NL)

In practice, there is a plethora of physical communication channels that share commonalities but also differences. Such channels include the traditional wireless communication channels, the newly proposed visible light communication (VLC) ones, the optical channels, and perhaps other communication channels, like underwater and biological ones. While some communications channels have been very well explored, other newly proposed, like some in the field of VLC, seem to be less well understood.

In our effort to understand new communications channels, it becomes apparent that there is an absence of a common framework that could allow us to analyze and utilize these communications channels in holistic manner and, therefore easily build upon prior knowledge. In this direction, such a framework should account for details about the transmission channel (e.g., linear, or time (in)variant) as well as the corresponding noise characteristic, that should form the basis to produce holistic and generalized information theoretical results (both at a link and a network level), as well as produce efficient coding schemes. Such coding schemes can be further categorized according to their practicality vs. optimality.

In such a framework, some of the aspects that need to be better explored are:

- The role of transmission "imperfections", as for example the non-linearities in optical systems. and how they affect both practicality, system design, practical codes and information theoretical results,
- Information theoretical results about the network aspects of such systems, including multiple access,
- Generic methodologies to achieve those limits,
- Coding approaches that are applied to structure of the transmitted information, instead of the traditional bit level coding (e.g., Space-Time-Super Modulation).

5.2 Discussion Group: Interference and Scheduling

Patrick Thiran (EPFL – Lausanne, CH)

1. Background
   Interference has a negative connotation, although information theory tells us that it does not need to be a bad thing. Wireless networks do not currently exploit these information theoretic findings, what are the steps needed to bring these advantages to reality?
2. Some fundamental challenges:
   - When can interference be overcome, and when will it remain an unavoidable pain? What are the system parameters that delineate this border, not only under an information theoretic perspective, but also under a networking perspective?
   - When and how to "reconfigure" the network so that it works with high SNR links in a regimes where interferences can be handled effectively?
   - Global knowldege is often needed in the above setting but is not available in practice. What can we achiever with only a local knowledge? What is the control information that needs to be exchanged with other network users and which is the most effective for coordinating them, possibly using out-of-band communication, in hybrid communication schemes?
3. Practical approaches
   None that was identified so far, but one can be felt is the translation of information-theoretic findings in results that can be exploited at the networking layers. Abstractions have played a key role in developing network protocols that work at a large scale, finding the proper abstraction model for these information-theoretic findings would be very helpful.
4. Different community perspectives
   Coping with interference is viewed as a problem well solved for N users for the multiple access channel by information theoreticians, but not by the other communities.
5. Initial solution directions:
   - Information theory provides strong results about handling interference for the multiple access channel model (packets from any user can be of interest for the receiver), but

the interference channel model (packets from only one user are of interest for a given receiver) remains open for $N > 2$ users.

- Current network protocols discard packets that have collided, but recent work on random access codes show a promising direction to make use of these packets with different random overlaps at high SNR. With a sufficient number of retransmissions, the packet could be recovered even if all these retransmissions resulted in a collision (zig-zag codes).

Participants

- Giuseppe Caire
TU Berlin, DE
- Izzat Darwazeh
University College London, GB
- Michelle Effros
CalTech – Pasadena, US
- Anja Feldmann
TU Berlin, DE
- Christina Fragouli
University of California at Los Angeles, US
- Seth Gilbert
National University of Singapore, SG
- Deniz Gündüz
Imperial College London, GB
- Martin Haenggi
University of Notre Dame, US
- Magnús M. Halldórsson
Reykjavik University, IS
- Longbo Huang
Tsinghua University – Beijing, CN
- Kyle Jamieson
Princeton University, US & University College London, GB
- Tomasz Jurdzinski
University of Wroclaw, PL
- Holger Karl
Universität Paderborn, DE
- Christina Kolb
Universität Paderborn, DE
- Bhaskar Krishnamachari
USC – Los Angeles, US
- Fabian Daniel Kuhn
Universität Freiburg, DE
- Muriel Médard
MIT – Cambridge, US
- Konstantinos Nikitopoulos
University of Surrey, GB
- Christian Scheideler
Universität Paderborn, DE
- Christian Schindelhauer
Universität Freiburg, DE
- Emina Soljanin
Rutgers University – Piscataway, US
- Vijay Subramanian
University of Michigan – Ann Arbor, US
- Patrick Thiran
EPFL – Lausanne, CH
- Tigran Tonoyan
Reykjavik University, IS
- Daniela Tuninetti
University of Illinois – Chicago, US
- Elif Uysal-Biyikoglu
Middle East Technical University – Ankara, TR
- Zhiying Wang
University of California – Irvine, US
- Roger Wattenhofer
ETH Zürich, CH
- Jörg Widmer
IMDEA Networks – Madrid, ES
- Dongxiao Yu
Huazhong University of Science & Technology, CN
- Michele Zorzi
University of Padova, IT
- Marco Antonio Zúñiga Zamalloa
TU Delft, NL