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Multi-receiver Uncoordinated Medium Access Ccontrol

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14. ABSTRACT
This grant went from January 15, 2017 to January 15, 2020 with ~$33,000 per year. This funding contributed to the PI, two post docs, one PhD student, and two masters students. The research group produced 9 peer reviewed papers during this period. This project was focused on studying wireless random access protocols and specifically, research within the context of uncoordinated or loosely-coordinated medium access techniques for new wireless applications such as sensors and machine-type communications networks.

From the final report: First, we have shown that the use of multiple receivers can be a promising option to improve reliability and spectral efficiency for networks with a large number of users that rely on data communications that is based on a simple slotted ALOHA policy. For an on-off fading channel model, we have been able provide exact expressions for uplink throughput and packet loss rate for an arbitrary number of relays, characterizing the benefits of multi-receiver schemes. In general, we show that while there are non-trivial tradeoffs, when one is considering the hierarchy level and coding scheme, the simplicity of such slotted ALOHA system can provide very attractive, low-complexity approach for communications. Second, we have derived analytical and exact expressions to quantify the key tradeoffs that characterize randomly distributed full-duplex slotted ALOHA networks. While in-band full-duplex has emerged as a promising solution, these results show that there are some very tight tradeoffs, and considering the complexity of full full-duplex transceivers for example for machine-type of communications the multireceiver ALOHA can exhibit very interesting and useful properties and optimal operation regimes. Third, as a part of our need to understand better the interference and signal classification opportunities related to the main theme of the pr

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"Multi-receiver Uncoordinated Wireless Medium Access Control"

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Abstract: Wireless random access protocols are attracting a revived research interest as simple yet effective solutions are required for new wireless applications such as sensor and machine-type communications networks, including also UAV and Satellite extensions for such networks. Such approaches have often highly different boundary conditions for complexity and coordination, while also requirements for robustness, spectral efficiency, and achieved bit-rate are also highly different when compared to dominant cellular and Wi-Fi data networks. Our project has pushed the boundaries of the field in some specific domains that already yield to practically usable insights and open a possibility for further research in the context of uncoordinated or loosely coordinated medium access. First, we have shown that the use of multiple receivers can be a promising option to improve reliability and spectral efficiency for networks with a large number of users that rely on data communications that is based on a simple slotted ALOHA policy. For an on-off fading channel model, we have been able provide exact expressions for uplink throughput and packet loss rate for an arbitrary number of relays, characterising the benefits of multi-receiver schemes. In general, we show that while there are non-trivial tradeoffs, when one is considering the hierarchy level and coding scheme, the simplicity of such slotted ALOHA system can provide very attractive, low-complexity approach for communications. Second, we have derived analytical and exact expressions to quantify the key tradeoffs that characterize randomly distributed full-duplex slotted ALOHA networks. While in-band full-duplex has emerged as a promising solution, these results show that there are some very tight tradeoffs, and considering the complexity of full full-duplex transceivers for example for machine-type of communications the multireceiver ALOHA can exhibit very interesting and useful properties and optimal operation regimes. Third, as a part of our need to understand better the interference and signal classification opportunities related to the main theme of the project we have conducted over the air measurements and satellite network simulations to understand how the signal classification and generally signal purity behaves. The most surprising preliminary result in this domain is that while Machine Learning based algorithms can help on classification and tracking of interfered signals, the selected feature space is much more important than the selection of the particular ML-technique.

Introduction: Random access protocols represent a simple yet effective solution to share a wireless channel among several users in many situations of practical interest. From this standpoint, scenarios characterized by radio devices generating traffic in an unpredictable or bursty fashion, as well as networks with a large population or a rapidly changing topology, are only some relevant instances in which scheduled access protocols may not be effective or viable. *The lack of coordination* at the MAC layer, however, typically comes at the expense of a less efficient use of the channel, due to two main factors. On the one hand, the receiver may get *a superposition of data units concurrently sent by different users.* These collisions likely prevent decoding and significantly lower the system throughput. On the other hand, allowing transmissions out of an agreed schedule makes it more difficult to cope with channel impairments and to maximize the spectral efficiency of performed communications.

The project aim was to study random access scenarios in which a multitude of users generate and send traffic over a shared wireless channel *in an uncoordinated fashion*. The main system topology is complemented by a set of receivers (or relays), which attempt to retrieve transmitted information, later to forward it to a central collecting unit (or sink). Such a configuration is representative for several applications of practical interest, ranging from tactical or disaster-relief networks to data gathering in machine-type communications. In the former case, receivers can be instantiated by UAVs or aircrafts hovering over an area of interest, while, in the latter, a constellation of satellites or ground access points may accomplish the task. During the project we also extended our consideration for totally random topologies relying on full-duplex transceivers, as this is another potentially useful ad hoc networking construction that provides an interesting comparison point for hierarchical random access topologies. We note that also in the case of our full-duplex transceiver analysis we rely on ALOHA-type of access. Finally, we were also addressing towards the end of the project the multiple receiver scenario with the prioritized traffic topology, e.g. assuming that only the low bit-rate but critically important information (e.g. collision-avoidance data from roads) were passed through multi-receiver structure, while high bit-rate data (e.g. video feeds) were passed through the more conventional coordinated single-links; this leads to very rich and interesting optimization problem, where robustness, cost, and size of the fleet have different optimality points depending on the system and application requirements.

Finally, one of the extended aims of the project was to understand in the context of flexible receivers how well the signals could be robustly classified under the interference conditions. In this case, we did not study the interference cancellation methods, that are well studies and are beyond the scope of the project, but focused on blind signal classification (modulation classification as the first aim of the project) under interference conditions.

The ultimate goal of the work is to develop *more robust uncoordinated wireless medium access control methods* that are also practically implementable. Such medium access work is in our opinion very important and provides opportunity for new, even fundamental, results. Generally, MAC work has not been done in the research community with high intensity as the highly coordinated cellular networks and non-power constrained CSMA in Wi-Fi was seen to provide reasonably optimal operational domain. However, our research premise has been to challenge this claim as the high coordination and/or non-power constraints are not applicable to many emerging applications, e.g. in the domain of sensor networks, smart cities, traffic surveillance, machine-to-machine communications, and UAV/Satellite type of networks.

The project results show that *uncoordinated access is generally warranted in many cases, where the dynamics of the situation do not allow any tightly coordinated medium access methods.*

Methodology: While the vast majority of our work has been theoretical and simulation based, we were also conducting over-the-air measurements of modulated RF-signals that were interfered with other signals. This work was done using both laboratory grade equipment (signal generators and analyzers) and SDRs (Software Defined Radios, mostly USRP-type of devices). The collected (I,Q)-sampled data provides capability to test different MAC and signal classification ideas in the future projects and we have put most of our data also openly available for other researchers (see de Vries et al. 2019).

Results and Discussion:

The main thrust of the project, especially in its first phase, was on understanding and developing methodology for low-complexity *uncoordinated* medium access, particularly in the context of slotted ALOHA (multi-)receiver concept. We have considered both single-receiver full-duplex uncoordinated networks and half-duplex multi-receiver networks. Especially at the time of project start these two approaches formed a natural comparison point – full-duplex attracting a lot of attention and promise, but being rather complex transceiver structure and multi-receiver system being lower-complexity but potentially less efficient. The main result emerging from the papers is that if we take the *uncoordinated networking* as the boundary condition (or premise for the application) the full-duplex approach can work, but it has very tight optimality conditions and taking into account also the complexity of the transceiver it might not be universally good solution, e.g. for UAV, tactical, or random machine-type communications (Munari et al., 2017; Munari et al. 2018). The multi-receiver architecture, especially if it is built as a hierarchical relay network, can provide robust connectivity with low complexity. However, the tradeoff for incoordination and low-complexity is that in the case of finite buffers non-trival tradeoffs will emerge and achievable (latency,bit-rate) boundaries seem to prefer the use of this sort of network for low-bit rate control or sensor data applications (Munari et al. 2017; Munari et al. 2019; Zucchetto 2019; Munari et al. 2020). On-going work to be submitted soon (Li et al. 2020), considers this sort of situation more specifically, where we deal with two different QoS/Service classes – critical service requiring robust low-bit rate access and non-critical service. We show that the grant-free ALOHA channel with multiple-receivers or deep interference cancellation structures can be made extremely robust, while losing delay and bandwidth efficiency. However, the high bit-rate services can be then provided with non-critical service channels that can use existing link-allocation based methods. The initial results indicate that the such dual system, especially if one considers non-terrestrial extension for LEO-satellite or separate altitude UAV-networks provide very flexible optimization space.

While the main thrust of the project has been on the above-mentioned research domain, there was related research we needed to conduct to understand better the interference patterns and effects. Thus, we made simulation based study to understand how to model the interference with the emerging NGSO satellite constellations, and made also specific study on some selected future constellations on how severe the interference is, i.e. how much there is need for medium access and interference coordination (Braun 2019). In fact, what we have found out is that the current relaxed approach is unlikely to be sustainable with very large constellations. Moreover, we conducted study on modulation classification with receivers that are receiving *modulated interference* from over-the-air transmissions (de Vrieze 2018). The main long-term value from this work is over-the-air realistic data set that can be used in the future to experimentally study different multi- or single-receiver scenarios. The data has been made publicly available. Our results show that DMC using different Machine Learning approaches can achieve a high classification accuracy even under the challenging real-world conditions of modulated co-channel interference and low-grade hardware. *However, this only holds if the training dataset fully captures the variety of interference and hardware types in the real radio environment*; otherwise, the DMC performance deteriorates significantly. Our work has two important engineering implications. First, it shows that it is not straightforward to exchange learned classifier models among dissimilar radio environments and devices in practice. Second, our analysis suggests that the key missing link for real-world deployment of DMC *is designing signal features that generalize well to diverse wireless network scenarios.* Thus, the main challenge is *not the machine learning methodology per se, but it is actually the training data and robust feature sets – something that seems to be missed in most of the literature outside the SIGINT community.*

List of Publications that resulted from your EOARD supported project:

a) papers published in peer-reviewed journals

A Munari, VG Douros, P Mähönen, "Mixed Nash Equilibria for In-Band Full-Duplex Networks", *IEEE Wireless Communications Letters*, vol. 7 (4), 502-505, 2018

A Munari, P. Mähönen, M. Petrova, "A stochastic geometry approach to asynchronous aloha full-duplex networks", IEEE/ACM Transaction on Networking, 2017

b) papers published in peer-reviewed conference proceedings

A. Munari, F. Clazzer and P. Mähönen, "On the performance of a full-duplex receiver for graph-based random access schemes," *2017 IEEE 18th International Workshop on Signal Processing Advances in Wireless Communications (SPAWC)*, Sapporo, 2017, pp. 1-6

C. Braun, A. M. Voicu, L. Simić, P. Mähönen, "Should We Worry About Interference in Emerging Dense NGSO Satellite Constellations?", *2019 IEEE International Symposium on Dynamic Spectrum Access Networks* (DySPAN), NJ, USA

C. de Vrieze, L. Simić, P. Mähönen, "The importance of being earnest: Performance of modulation classification for real RF signals", *IEEE International Symposium on Dynamic Spectrum Access Networks* (DySPAN), Seoul, South-Korea, 2018 (*extended version to be submitted journal*)

D. Zucchetto, A. Munari, A. Zanella, "On the Optimal Rate of Ad Hoc ALOHA Networks", IEEE Wireless Communications and Networking Conference Workshop (WCNCW), 2019

A. Munari, F. Clazzer, "Modern Random Access for Beyond-5G Systems: a Multiple-Relay ALOHA Perspective", IEEE 3rd Balkan Conference on Communications and Networking, 2019

c) papers published in non-peer-reviewed journals and conference proceedings

d) conference presentations without papers

e) manuscripts submitted but not yet published

A. Munari *et al.,* "Multiple-Relay Slotted ALOHA: Performance Analysis and Bounds," 2020 (attached)

f) manuscripts to be submitted

J. Li, P. Mähönen, "*Throughput Optimization for Heterogeneous Data in UAV-based Hierarchical Highway-VANET*"