TACTILENet

Towards Agile, effiCient, auTonomous and massIvely LargE Network of things

WP2- (Analysis and Development of Communication Technologies)

D2.4 D12 Report on Short Block Coding

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1 Summary

We are witnessing an unprecedented worldwide growth of mobile data traffic that is expected to continue at an annual rate of 45% over the next years, reaching 30.5 exabytes per month by 2020. To handle this "data tsunami", the emerging 5th generation (5G) systems need to improve the net- work performance in terms of energy consumption, throughput and user experienced delay, and at the same time make a better use of the network resources such as wireless bandwidth and backhaul link capacity. The landscape toward 5G wireless communication is currently unclear, and, despite the efforts of academia and industry in evolving traditional cellular networks, the enabling technology for 5G is still obscure. The vision for the 5th generation of mobile networks (5G) includes at its heart the Internet of Things (IoT) paradigm, leading to a new era of connectivity where billions of devices exchange data and instill intelligence in our everyday life. The EU has set out to play a leading role in developing 5G technologies by consolidating and building upon the most important research and innovation results attained in previous research programs. As depicted in Figure 1 the objective of the **TACTILENet** project is to bring together the complementary expertise of European and third-country partners in order to lay the foundations for addressing basic issues in several facets of 5G networking. The cross-fertilization among partners will contribute to the ongoing research efforts by jointly identifying ambitious yet feasible goals for 5G system, addressing some of the fundamental research problems in achieving these goals, and finally, by designing and analyzing a suite of protocols.

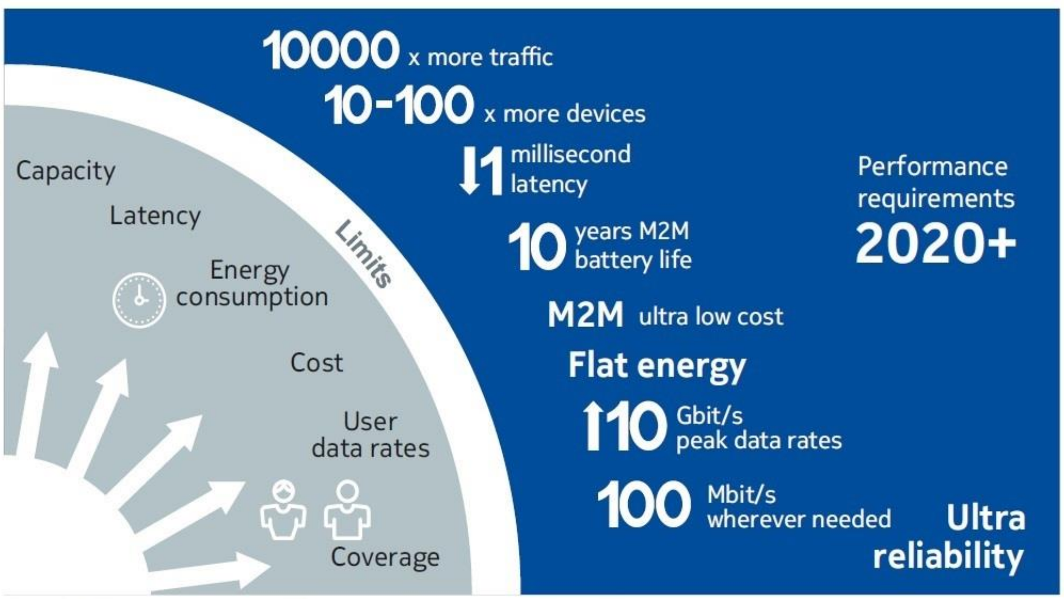

Figure 1. Vision of Tactilenet project

TACTILENet represents an opportunity for the European research and industry to take the lead in Information and Communication Technologies, capitalizing on the area in which Europe always had the potential to succeed, namely wireless networking. Europe possesses significant potential in individuals and research groups that can bring real breakthroughs in the way wireless networks are perceived, operated and controlled. We believe that through

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collaboration with third country partners that are experts in the field, **TACTILENet** can provide technological advance to the European industry. Research within **TACTILENet** can also create new business opportunities for SMEs since the novel techniques that will be developed will provide significant opportunities. One major example toward this direction is to design novel spectrum access schemes and interference management policies. **TACTILENet** will provide strong incentives for collaborative research in Europe. The participating partners possess complementary expertise in different aspects of networking and this project will increase their competitiveness in Europe and in the world. With the appropriate support, TACTILENet will have significant impact in terms of shaping the landscape of wireless communications in Europe. The fundamental premise of integrating high- density access points together with thousands of devices communicating at low data rates, and the novel integration of quality-of-experience (QoE) measures for a range of application scenarios that will prevail are expected to incur: 1) design of interference management techniques for ultra-dense wireless environments by adapting coordinated multipoint (CoMP), cooperation, and interference alignment techniques, 2) strengthening of interoperability of various technologies, such as C-RAN, CIoT, etc., that will be universally supported in a seamless fashion, 3) easiness in deployment due to the self-configuration of the C-RAN architecture, and to a lower cost for the deployment and running of the baseband equipment shared by a group of remote radio heads.

2 Objective

The objective of this report is to provide an overview of the research problems on machine type communications and possible use of short block coding for enabling such communications.

The reported work is the outcome of the activities performed under Task 2.4 "Machine-Type Communications" of GA, Annex I, part A. The outcomes of this work has close ties to Tasks 2.1, 2.2 and 2.3 (WP2) as well as Tasks 3.1, 3.2 and 3.3 (WP3) of GA, Annex I, part A.

The key findings of this work are: 1) Application specific requirements are significantly more essential in optimizing machine-type communications. In particular, in this work, we analysed two completely different applications, i.e., Virtual Reality (VR) communications and sensor data collection. We propose and analyse methods for each type of applications. 2) Random access mechanisms should be completely overhauled for taking into account short but latency sensitive machine type communications. 3) Sophisticated physical layer solutions such as beamforming adaptation using machine learning can significantly improve the performance. The report is the last deliverable related to WP2 and thus, completing successfully the objectives of WP2.

The technical part of the report is organized as follows. In Section 3, we provide a summary on the state-of-the-art short block length coding and machine-type communications. In

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Section 4, a new method and apparatus for VR social media networks is developed and analysed by taking latency as the relevant QoE performance measure. In Section 5, we investigate an optimized design of medium access protocol that aims at much tighter coupling between the data and control planes to efficiently transfer short length data blocks. In Section 6, we design and analyse a mm-wave UAV-based broadcast machine-to-machine broadcast data delivery scheme by employing information-theoretic channel capacity bound to determine the accessibility of sensor nodes from UAV. In Section 7, a new method and apparatus for UAV sensor data collection is developed and analysed by taking latency and energy efficiency (in terms of using backscatter sensor nodes) as relevant performance metrics.

3 Current state-of-the-art

3.1 Short Block Coding

Most of the recent advances in the design of highspeed wireless systems are based on information-theoretic principles that demonstrate how to efficiently transmit long data packets. However, the 5G and beyond 5G wireless systems, will need to support novel traffic types that use short packets. For instance, short packets represent the most common form of traffic generated by sensors and other devices involved in machine-to-machine communications. Furthermore, there are emerging applications in which small packets are expected to carry critical information that should be received with low latency and ultrahigh reliability. Current wireless systems are not designed to support short packet transmissions. For example, the design of current systems relies on the assumption that the control information (metadata) is of negligible size compared to the actual information payload. Hence, transmitting metadata using heuristic methods does not affect the overall system performance. However, when the packets are short, metadata may be of the same size as the payload, and the conventional methods to transmit it may be highly suboptimal. As a result, the need for such systems that operate under strict latency and reliability constraints has recently caused a rising interest in protocols and error correction schemes with short and medium-block length codes (i.e., codes with dimension k in the range of 50 to 1000 bits) for the transmission of small amounts of data. Note that although short packets reduce latency, they in turn cause a severe loss in coding gain. [ODSLSL17] [LGNJ16] [DKP15]

In recent years, considerable efforts have been spent in the design of powerful short error-correcting codes, and in understanding the fundamental performance limits in the regime of small block size. When the design of short iteratively-decodable codes is attempted, it turns out that some classical code construction tools which have been developed for turbo-like codes tend to fail in providing codes with acceptable performance. This is the case, for instance, of density evolution and extrinsic information transfer (EXIT) charts, which are well-established techniques to design powerful long low-density parity-check (LDPC) and turbo codes. The issue is due to the asymptotic (in the block length) nature of density evolution and EXIT analysis which fail to properly model the iterative decoder in the short block length regime. However, competitive LDPC and turbo code designs for moderate-length and small blocks

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have been proposed, mostly based on heuristic construction techniques. While iterative codes retain a large appeal due their low decoding complexity, more sophisticated decoding algorithms are feasible for short block s leading to solutions that are performance-wise competitive (if not superior) with respect to iterative decoding of short turbo and LDPC codes. [LGNJ16] [SWJVV16].

It is appropriate at this point to formally define what is meant by short/long packets. The transmission of a packet is a process in which the information payload (data bits) is mapped into a continuous-time signal, which is then transmitted over the wireless channel. A continuous-time signal with approximate duration T and approximate bandwidth B can be described by $n \approx BT$ complex parameters. It is then natural to refer to n as the packet length, i.e., the number of degrees of freedom (channel uses) that are required for the transmission of the information payload. [DKP15]

A channel code defines a map between the information payload and the signal transmitted over the n channel uses. The task of a wireless receiver is to recover the information payload from a distorted and noisy version of the transmitted signal. A fundamental result in information theory [S48] tells us that when n is large (long packets), there exist channel codes for which the information payload can be reconstructed with high probability. Intuitively, when n is large both the thermal noise and the distortions introduced by the propagation channel are averaged out due to the law of large numbers. However, when n is small (short packets) such averaging cannot occur. Another defining element of long packets, besides the large number of channel uses, is the fact that the payload contained in a packet is much larger than the control information (metadata) associated with the packet. As a consequence, a highly suboptimal encoding of the metadata does not deteriorate the efficiency of the overall transmission (see Fig. 1. a)). On the contrary, when the packets are short, the metadata is no longer negligible in size compared to the payload (see Fig. 1. b)). [LDCUL17] [DKP15]

The possibility of breaking the frame into shorter blocks can be briefly discussed as follows: [JT04] [LC04]

A frame of length N_f may be broken into $\frac{N_f}{n}$ codewords from a (n, k) code. Here it is assumed that k is chosen to divide the number of information symbols in the frame. Assume that based on a bound or on simulations of the particular code, we know the probability of decoding error, P_{err}. Then, if the frame consists of $\frac{N_f}{n}$ blocks, and the noise is independent, the probability of a correct frame is $P_{ue} = 1 - (1 - p_{err})^{\frac{N_f}{n}}$. Thus, we can get a very small probability of undetected errors only if the error rate on the channel is very small, and the system is not very efficient. In order to improve the performance, we may restrict the number of errors corrected in each block. However, with a probability of decoding failure P_{fail} we similarly get a bigger probability of frame error. Moreover, if the frame consists of $\frac{N_f}{n}$ blocks,

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and the noise is independent, the probability of frame error is $P_{fe} = 1 - (1 - P_{fail})^{\frac{N_f}{n}}$. For the situation of main interest here, it is more efficient to combine error correction with a frame check sequence. By using 16 or 32 bits for this purpose it is possible to make the probability of undetected error very small, and we can still use the full power of the short block code for error correction.

To achieve ultra-high reliability and low latency (URLLC), the design and implementation of short block length channel codes are very critical. According to literature, the considered candidate channel codes include Polar codes, Turbo codes, LDPC codes, Convolutional codes, and BCH codes, which can be compared in terms of block error rate under optimal decoder, rate performance under practical decoders, and algorithmic complexity of decoding algorithms. It is shown that BCH codes provide the highest reliability under optimal decoding, since they have the highest minimum Hamming distance. Polar codes with successive cancellation list decoding provide a reliability of $(1 - 10^{-4})$ with only 0.5 dB gap to the normal approximation with reasonable complexity, however better results might be achieved with reduced complexity ordered statistics decoder (OSD) and BCH codes with the same level of complexity. [WABM16] [WABM17] [SSAMYMHLLJV18].

3.2 Machine Type Communications

To ensure connectivity alongside cost effective routing, [STC17] conducts a feasibility study of device-to-device (D2D) communication by analyzing the coverage probability and average data rate of a three-hop machine-to-machine (M2M) network that is deployed along with user equipment's (UEs). In [KS16] a coding framework for a multicast scenario that uses joint channel and PHY layer network coding is proposed in a network of three devices in which they exchange data via a relay or another device in vicinity. It is shown that the coding strategy is capable of achieving near-optimal sum rate throughput and a scalable version of the strategy is extended for large number of M2M devices. An energy efficient resource control protocol that transitions the state of the radio resource control depending on pre-determined parameters based on the traffic pattern is proposed in [QQIT15] and simulation results showed that the protocol can reduce both the energy consumption and the signaling overhead. For a M2M devices operating in a cellular infrastructure, downlink performance of the millimeter-wave nonorthogonal multiple access (mmWave-NOMA) transmission scheme is investigated in [LMZM18] for three different device pairing scheme and the performance of the schemes in terms of outage probability and sum rate is derived. It is concluded that mmWave-NOMA transmission scheme improves outage probability compared to mmWave with orthogonal multiple access schemes.

In [YSHQY17] for a random-access protocol in a multiple-input multiple-output (MIMO) data transmission system, under delay constraint optimal number of access request slots is calculated to maximize the throughput. [LXCJ18] addresses the massive access needs of MTC by aiming to mitigate the collison of MTC devices that communicate with a base station. A

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clustering algorithm based on the locations of MTS devices and service requirements is proposed that is shown to significantly decrease collision probability. [SBFMBD18] exploits the possibility of using multiple waveforms offered by 5G standard to consider multiple combination of waveforms in a D2D communication of MT devices and UEs in asynchronous manner that reduces the signaling overhead of massive number of devices. In [LYSSZY17], based on the different functions and quality-of-service requirements of the MTC devices, physical M2M network is virtualized by slicing the network into multiple virtual M2M network. For the virtualized network, a decision-theoretic approach is employed to optimize the random-access strategy. For a large number of devices transmitting to a massive MIMO base station with hundreds of antennas, in [CBSLO17], device activation probability and pilot lengths are optimized to maximize the sum-rate performance.

To increase the probability of successful access of MTC devices, [KLC17] introduces the notion of virtual preambles of MTC devices that associates each with a random-access channel and show that the proposed scheme can outperform the existing preamble-based scheme in terms of collision probability, access delay, and access blocking probability. In [AG18] a collision aware random-access protocol is proposed that adaptively change the access probability based on early collision detection to achieve maximum throughput. [ZD18] stablishes a double-queue model that can consider the behavior of each MT device. The throughput of the network is maximized by properly choosing the back-off parameters. In [IZQT16] effect of unknown channel access on the automatic repeat request (HARQ) process is studied in a coverage extension by a relay scenario.

[RKBLV17] studies the fundamental limit and scope of using solar cell or photovoltaic harvesting-based M2M communication systems by deriving theoretical bounds on the Shannon capacity theorem. A new grant-free NOMA scheme is proposed in [MAWCZZG18] by dividing the data packet of each user into segments and by generating redundancy segments. Then multiple orthogonal spreading codes are used to spread the data symbols of different segments so that collision can occur on the segments using identical spreading codes. In [ALMY17] energy harvesting MT devices use D2D communication as an underlay to the cellular network and the trade-off of the amount spectrum occupation by MT devices versus the amount of harvested energy is studied.

To prevent random access overload in M@M systems [WW15] proposes a scheme that uses both access class barring (ACB) and timing advance information and maximize the expected number of MTC that are successfully served in a slot. In [CBY18], by estimating the maximum access delay and average number of preamble transmissions for distributed queueing-based random access (DQRA) protocol, random access performance is improved. [XCY18] surveys recent resource management protocols conducted to address the diverse requirements of machine type communications while addressing the issues regarding various technologies that is foreseen for M2M networks. Finally, survey of [WZRYZHY18] describes the evolution of 3GPP LTE in control channel design.

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4 Latency optimization in VR Mobile Social Networks over Wireless Cellular Systems

4.1 Motivation and Problem Definition

Virtual reality (VR) is considered to be one of the key use cases for 5G [VR1, VR2]. Furthermore, VR is one of the flagship use cases with respect to latency and interaction among the users and things within the future Tactile Internet. Immersive social interactions of mobile users are soon to be enabled within a virtual space, by means of virtual reality (VR) technologies and wireless cellular systems. In a VR mobile social network, the states of all interacting users should be updated synchronously and with low latency via two-way communications with edge computing servers. A key new element of this challenging problem is the discrepancy between virtual and physical locations of the participating users. In fact, traffic is generated by VR communities in a virtual space, but the supporting network resource for communication and computation are located within the physical network infrastructure. Therefore, the users in the same VR community may not always be co-located in the physical space.

A simple scenario that captures these tradeoffs is given on Figure 2. The traffic is generated by VR communities in a virtual space, but the supporting network resourcea for communication and computation are located within the physical network infrastructure. Therefore, the users in the same VR community may not always be co-located in the physical space. In Figure 2, user C belonging to VR community 1 is close in the physical space to user D affiliated to VR community 2, but far from users A and B in VR community 1. The discrepancy between the virtual and physical topologies affects resource allocation over both Radio Access Network (RAN) and backhaul.

We studied the problem of supporting a VR mobile social network over a multi-cell wireless cellular system with the goal of minimizing the end-to-end latency. Specifically, we focus on the problem of minimizing the end- to-end latency via the bandwidth allocation of the uplink and downlink channels used for communication between users and computing servers. To this end, we formulate a simple model based on a linear cellular topology, depicted on Figure 3that captures the interplay between the social interactions within the VR mobile social network and the location of the computation and communication resources within the physical network. The average end-to-end latency is evaluated by accounting for the contributions of uplink, downlink, and backhaul transmissions, as well as for processing times at the servers. The resulting latency is minimized through a stochastic optimization technique.

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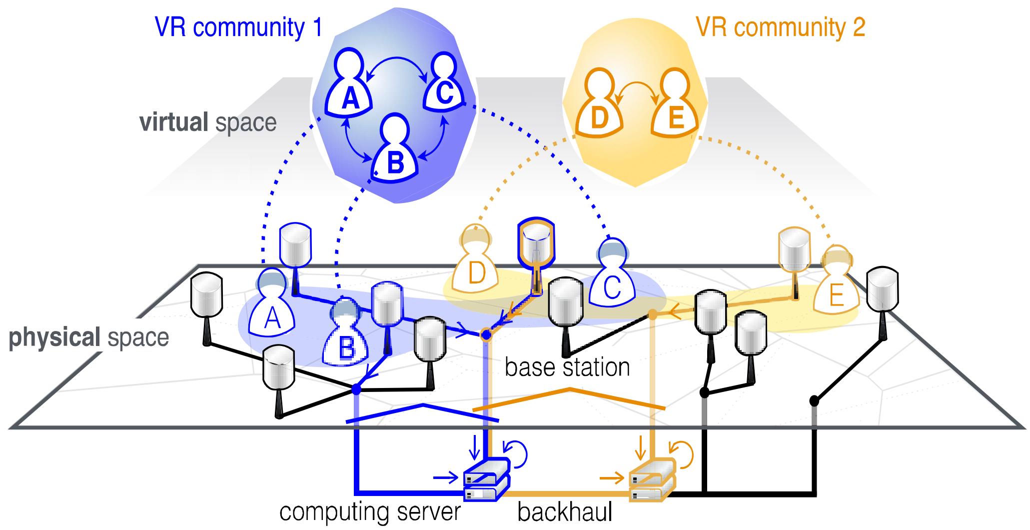

Figure 2 Illustration of VR mobile social network, where the traffic is generated by virtual-space user interactions and supported by a physical cellular network.

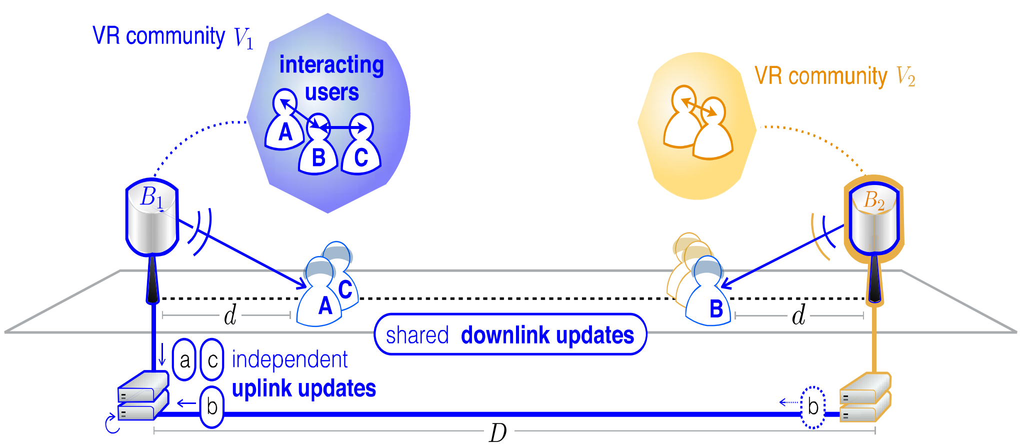

Figure 3 An illustration of a VR traffic flows in a one-dimensional physical network model. VR users A, B, and C are interacting within VR community V1. Their uplink updates a, b, and c are sent to the cloud computing server at B1 via unicast transmissions. The resulting downlink update needs to be sent to all three users for synchronous interactions via multicast transmissions.

4.2 System End-to-End Latency Minimization

The network under study comprises a set of N users K and two Base Stations (BSs) denoted by B_1 and B_2. Each BS is equipped with a computing server that supports a single VR community. The computing server for VR community V_i is located at BS B_i. In the virtual space, each VR community V_i includes a subset of users representing a fraction p_{V_i} of the set of users, with $p_{V_1} + p_{V_2} = 1$. Furthermore, a subset of users associates with BS B_j for both uplink and downlink transmissions in the physical space, representing a fraction p_{B_j} of the set of users, with $p_{B_1} + p_{B_2} = 1$. There are four types of possible user assignments in the virtual

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and physical spaces, partitioning the set of users into four subsets, corresponding to the four possible associations to V_i and B_j. The number of users associated with V_i and B_j is denoted by N_{ij}, corresponding to the fraction of users $p_{ij} = \frac{N_{ij}}{N}$.

The two BSs are located at the edges of a one-dimensional physical space with length and are connected by a wired backhaul. The BSs use disjoint spectrum bands, hence not interfering with each other. The BS B_j assigns orthogonal bands to uplink and to downlink following Frequency Division Duplex (FDD). In the uplink, a BS serves all the associated users via Frequency Division Multiple Access (FDMA) using *unicast* transmissions. In the downlink, instead, each BS uses orthogonal *multicast* transmissions in order to update the users in the two VR communities. Each user is associated to the closest BS. In this first study on th subject, in order to obtain worst-case performance results, all users are assumed to lie at the maximum distance allowed, i.e. right in between the BSs. For the given physical distance d between a BS and the assigned user, the signal-to-noise ratio (SNR) is determined by path loss attenuation d–α for α ≥ 2 and by independent Rayleigh fading. We assume the use of type-I Hybrid Automatic Repeat reQuest (HARQ), while the instantaneous SNR information is unknown at the BSs.

For a single state update, the VR traffic of user o is characterized by the following phases.

• Step 1 (Upload) – The user uploads its update message with size b_{up} bits to the associated BS. If user *o* is of cross-type, i.e. the virtual and the physical association are different and $j \neq i$, then the the uplink data is forwarded to the desired computing server through the inter-BS wired backhaul;

• Step 2 (Compute) – The computing server located at a given BS collects all input data from user *o* as well as from its interacting users from the same VR community, and then produces their synchronous output states;

• Step 3 (Download) – The output states are updated with a common message of size b_{dn} bits to all interacting users from the same VR community through wireless and, for cross-type users, backhaul links.

Since the computing server needs to collect data from all users in a given VR community, the delay prior to computing is limited by the user with the worst uploading delay in VR community, which is the key observation in the model.

The central quantity to be minimized is the average end-to-end latency for a user associated to virtual community V_i and the BS B_j:

$$T_{ij} = T_{ij}^{up} + T_i^c + T_{ij}^{dn}$$

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where T_{ij}^{up} is the average uploading delay, T_i^c is the average computing delay and T_{ij}^{dn} the average downloading delay. The objective is to optimize the spectrum allocation $\boldsymbol{w}$ in order to minimize the average end-to-end latency that encompasses all types of users, for a given configuration $\boldsymbol{N}$ of associated users:

$$\boldsymbol{w}^* = \text{argmin} \sum_{i=1}^{2} \sum_{j=1}^{2} p_{ij} T_{ij}(\boldsymbol{w}, \boldsymbol{N})$$

for a given total allocated bandwidth.

In order to evaluate the impact that different user configurations have on this minimization, we define the cross-type ratio ρ_c as the fraction of the users that are of cross-type. We consider the symmetric setting with equal loads of the two BSs and with an equal fraction of cross-type users for each BS. Figure 4 shows the average end-to-end latency versus the cross-type user ratio ρ_c. The latency is seen to increase monotonically with ρ_c owing to the increasing backhaul delays of cross-type users. The proposed optimal uplink spectrum allocation is able to partially compensate for the backhaul delays by providing more spectrum to cross-type users. Note that optimal uplink spectrum allocation cannot improve the latency performance when we have $\rho_c = 0$, i.e., no cross-type users, or $\rho_c = 1$, i.e., all cross-type users. For such cases, all uploading user delays are identically distributed, and it is thus not possible to prioritize spectrum allocation to any group of users.

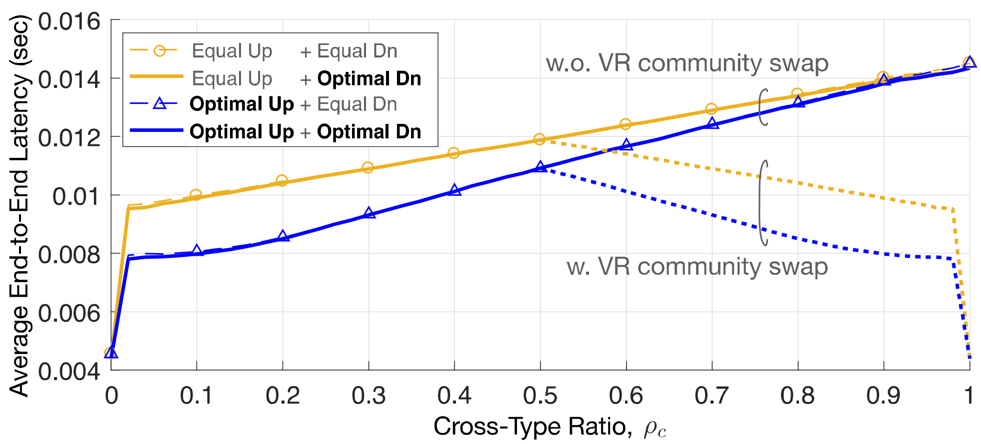

Figure 4 Average end-to-end latency of a uniformly randomly selected user as cross-type ratio ρ_c increases, where cross-type users connect to the BS that does not run the corresponding VR community.

5 Random Access Schemes in Wireless Systems with Correlated User Activity

Massive Machine-Type Communications (mMTC) serves as an important service type in 5G. In contrast to traditional uses of communication systems machine-type traffic is characterized by a very large number of devices, small packet sizes and possibly strict latency and reliability

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requirements. Furthermore, machines are likely to produce more correlated and predictable traffic pattern. In this work, we investigate how knowledge about the user activity correlation can be used to improve the throughput of ALOHA-like random access protocols, and consequently reduce the latency and higher reliability.

The problem is studied in a classical ALOHA setting comprising N users and in which each frame is divided into K slots. A subset of the N users are active in each frame, and transmit in a slot. If more than one user transmit in the same slot in a given frame, all transmissions are in that slot are lost. The users are active according to some joint probability distribution $\Pr(x_1, x_2, \dots, x_N)$, where $x_n = 1$ if user n is active and $x_n = 0$ otherwise. The paper introduces a combined scheduling and random access procedure, in which each user is assigned to one of the K slots, and will transmit in this slot during activation.

The overall idea is to assign users to slots in such a way that users that are likely to transmit in the same slot are assigned distinct slots, while users that are anti-correlated are assigned the same slots. This way, the probability that to two users transmit in the same slot is reduced.

Two heuristic allocation algorithms are proposed (*min-sum* and *min-max*), which make use of the probability that two users transmit in the same slot (this is assumed to be known). The algorithms are evaluated in a scenario with spatio-temporal correlation. Specifically, users are located in an area with side length $L = 100$ in which events are generated according to a Poisson point process. All users that are within a certain radius, $r = 15$, of an event transmit in their assigned slot in the following slot. The results show that the throughput can be significantly increased compared to the classical ALOHA setting (Figure 5). Furthermore, since the probability of user activation is known, the base station can reduce the network load by declaring that active users should transmit only with a certain probability (referred to as *scaled* in Figure 6). This leads to a higher throughput in the region where the system is overloaded compared to classical ALOHA.

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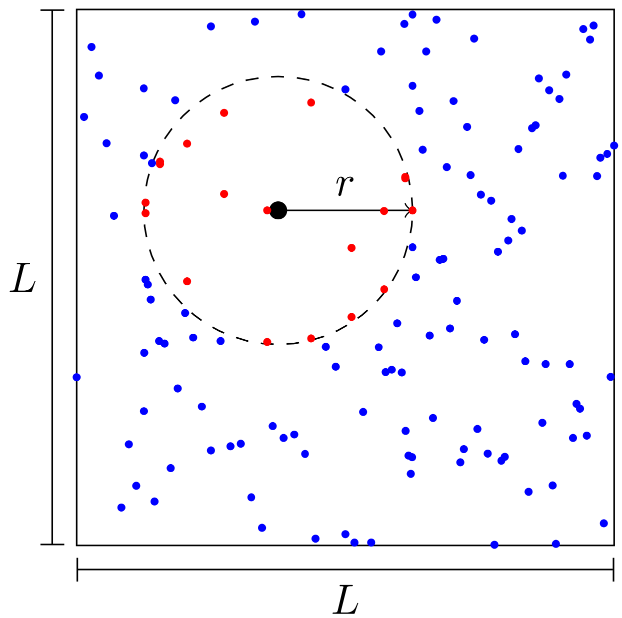

Figure 5 Illustration of the spatio-temporal traffic model where the black circle indicates an event, and the red dots are active devices.

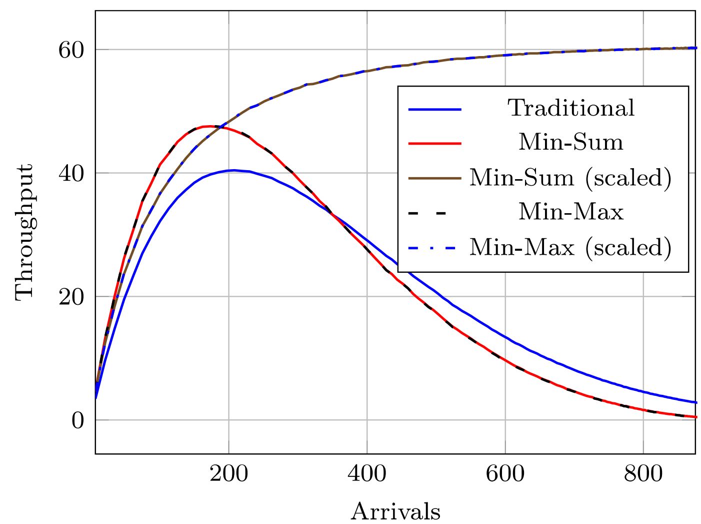

Figure 6 Throughput in the spatio-temporal scenario with 150 slots and varying average arrivals.

6 Single RF Beamforming in mmWave MIMO-UAV Using Machine Learning

In this work, a mm-Wave downlink scenario is considered which composed of a drone base station (DBS) and multiple users. DBS is equipped with an M element antenna array and serve K single antenna users. For simplicity it is assumed that the antenna array is arranged on a uniform linear array (ULA) and the spacing between antennas is half the wavelength. We assume that depending on the specific geometry of the environment and 3D antenna radiation

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pattern, some users fall in to the coverage region. We assume a LOS path between the users and drone and the channel model for the user n becomes

$$h_n = \sqrt{M}\frac{\alpha_n \boldsymbol{a}(\theta_n)}{\sqrt{PL(\theta_n)}}$$

where α_n shows the small-scale fading effect, $\boldsymbol{a}(\theta_n)$ is represents the steering vector, $PL(\theta_n)$ is the path loss, and θ_n is the elevation angle of user n. The drone uses a beamforming vector of $w(\phi) = a(\phi)$ and the term $|a(\theta_n)^H \boldsymbol{w}(\phi)|^2$ is called the antenna gain. The received LOS SNR by user n is

$$SNR_n^{LOS} = \frac{P_t \alpha_n |\boldsymbol{a}(\theta_n)^H \boldsymbol{w}(\phi)|^2}{N_0 (h_d^2 + r_n^2)^{\eta_L/2}}$$

where N_0 and $r_n = h_d \tan \theta_n$ denote the noise power and horizontal distance between DBS and the nth user and h_d is the drone's altitude. User n is in the coverage of the drone if $SNR_n^{LOS} \geq \gamma_n$. The objective is to design the beamforming vector so that maximum number of users is covered by the drone. Let $u_n(\phi)$ be an indicator that represents the coverage state of user n when the beamforming angle is ϕ. Denote by $U(\phi) = E\{\sum_{n=1}^{N} u_n(\phi)\}$ as the expected number of users that can be served by the DBS whent the beam angle is ϕ. The optimization problem becomes

$$\max_{\phi} U(\phi)$$

Due to the complicated nature of the optimization problem as well as many unknown and heterogenous statistics in the network, we resort to multi-armed bandit problem as a solution approach. More specifically we use Thompson sampling (TS) which is known for its judicious exploration strategy by using Bayesian inference in contrast to ϵ-greedy algorithm. For a Rayleigh fading with 500 users in the network the regret of TS and ϵ-greedy algorithm is depicted in Figure 7. We observe the superior performance of the TS in learning the optimal beam angle deployed by DBS.

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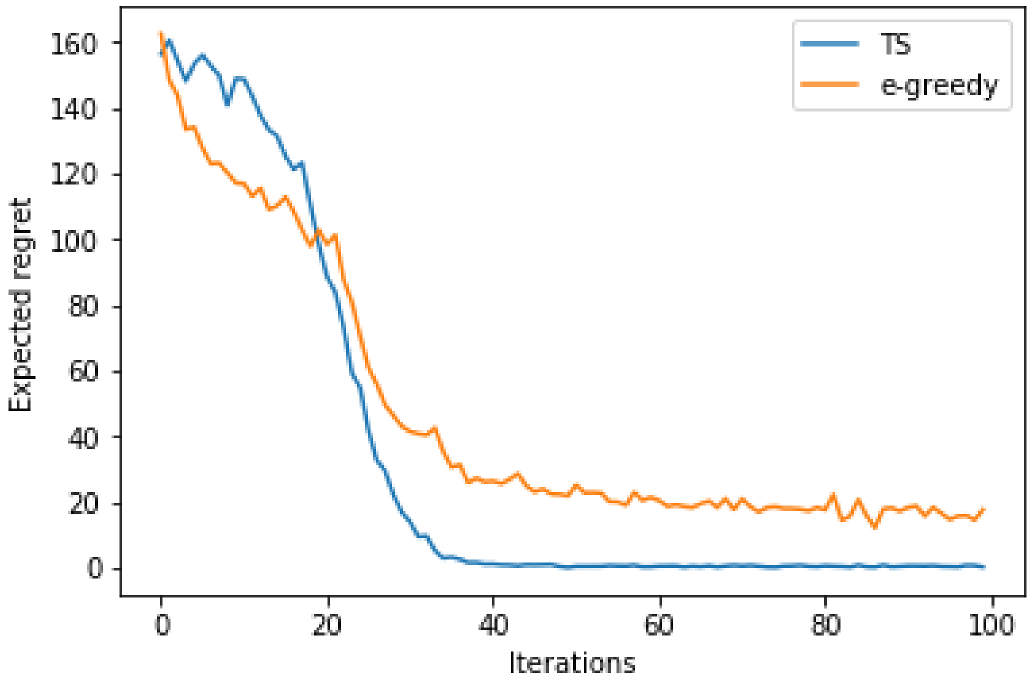

Figure 7 Expected regret of TS and ϵ-greedy algorithms

7 UAV Data Collection over NOMA Backscatter Networks: UAV Altitude and Trajectory Optimization

In this work, we studied the performance of a novel network model where a NOMA-based long-range backscatter network is facilitated with an aerial power station and data collector. Our objective was to investigate the relationship between the optimal altitude of the UAV and the total number of successfully decoded bits and the UAV's flight time. To the best of the author's knowledge, this is the first work in the literature which studies the UAV-enabled backscatter networks where the objective is to maximize the number of successfully decoded bits while minimizing the flight time by finding the UAV's optimal altitude. The results showed that for a selection of parameters, there exist an optimal altitude where the ratio of the number of successfully decoded bits to the flight time is maximized. To be more precise, we considered a UAV-assisted backscatter network where N backscatter nodes (BNs) are distributed independently and uniformly (i.e., binomial point process) with a sufficiently high density in a target area on the ground and there is a single UAV acting as both mobile power transmitter and information collector. We assume that the UAV is equipped with a directional antenna with fixed effective illumination angle (or beamwidth) and it hovers over the target area for a duration of T_f. During the total flight time T_f, the UAV continuously broadcasts a single carrier RF signal with fixed power P_u to all BNs on the ground, i.e., it acts as carrier emitter. On the ground side, the BNs become active and utilize the received RF signal to backscatter their data to the UAV simultaneously based on power-domain NOMA scheme. In order to improve the number of successfully decoded bits, the UAV may need to lower its

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altitude to get closer to BNs, and thus, it cannot cover the entire target area in a single time slot; in this case, the target area is divided into W sub-regions each with the same radius such that at an altitude of H. Consequently, the total flight time will be divided into W sub-slots (ignoring the time it takes to fly from one sub-region to the other).

Our objective is to maximize the total number of successfully decoded bits by the UAV while minimizing its flight time, by finding an optimal altitude H^*. We consider an application scenario, where data from all BNs within the subregion should be successfully decoded. Otherwise, the whole sub-region data is discarded. This metric is appropriate when each BN's data is unique and uncorrelated, and thus, it is a requirement to collect data from *all* BNs. Hence, we define the network throughput $C(H)$ as the ratio of the total number of successfully decoded bits during all time sub-slots (i.e., in all sub-regions) to the total flight time: $C(H) = \frac{\sum_{l=1}^{W(H)} C_l(H)}{T_f(H)}$, where $C_l(H) = N_l(H)TR(1 - P_{out}^{(s_l)}(H))$ is the number of successfully decoded bits at sub-region $s_l, l = 1, \dots, W$, and also $P_{out}^{(s_l)}(H)$ is the outage probability corresponding to sub-region s_l, which is determined as $P_{out}^{(s_l)}(H) = 1 - \Pr\left(SINR_{k_1}^{(s_l)} \geq \gamma, \dots, SINR_{k_{N_l}}^{(s_l)} \geq \gamma\right)$: where γ is the a given signal-to-interference-plus-noise ratio (SINR) threshold necessary for successful decoding and $SINR_{k_i}^{(s_l)}$ is the SINR value for the backscattered signals from BN $k_i, i = 1, \dots, N_l,$ received at the UAV which is calculated as $SINR_{k_i}^{(s_l)} = \frac{P_u \mathcal{E}_{k_i} h_{k_i}^2 d_{k_i}^{-2\alpha}}{\sum_{j=k_{i+1}}^{k_{N_l}} P_u \mathcal{E}_j h_j^2 d_j^{-2\alpha} + \mathbb{N}}$. Note that we assume that the backscattered signal by k_1 is the strongest signal and gets decoded at the UAV first; on the other hand, k_{N_l}'s signal is considered to be the weakest one and gets decoded after all the stronger signals are decoded. Hence, the optimization problem can be expressed as

$$\max_{H \epsilon \partial} C$$
$$s.t. 1 \leq W \leq W_{max}$$

where $\partial \epsilon \{H_{min}, \dots, H_{max}\}$ is a set of discrete altitudes. The set of altitudes is determined by the operational requirements of the UAV. Furthermore, the problem is a fractional programming (FP) problem with non-differentiable fractional objective function. Since the cardinality of the set of altitudes that a UAV can hover over is finite, and the locations of BNs are known a priori, we use exhaustive search to determine the optimal solution.

Finally, as illustrated in Figure 8, the simulation results showed that with lower SINR thresholds, there exists an optimal altitude where the throughput is maximized, and as the sensitivity of the SIC decoder at UAV increases, the throughput increases as well. As the altitude is high, the number of BNs backscattering is also high, but the received power from each are close. This reduces the probability of correct decoding. However, if the altitude is low, then even if there are fewer incoming transmissions from the BNs, the total flight time of the UAV is high, reducing the throughput. In Figure 8, we also examine the performance of

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the network throughput with respect to UAV's altitude H with different BNs backscatter reflection coefficients. The figure shows that selection of the range of reflection coefficients have a significant impact on the throughput. When the reflection coefficients assigned to BNs are not the same and they are taken from the set $[0.1, 0.99]$ the throughput, in the case $\gamma = -4$ dB, improves by more than 40% compared to the case when all reflection coefficients are the same. When the difference between the reflection coefficients increases, the received power of backscattered signals from BNs are further apart from each other, and thus, the SIC decoder will make fewer decoding errors. Moreover, in Figure 9, we evaluated the performance of the throughput value at the optimized altitude with respect to the effective illumination angle θ, under different considerations for the total number of BNs $N = 10, 40, 60,$ and 100. The figure shows that the throughput at the optimized altitude monotonically increases as θ grows. When θ value is low, the UAV operates at a higher altitude to cover the target area, hence, the path-loss effect is notably high reducing the throughput. However, in high θ values, the UAV operates at a lower altitude. Thus, the throughput increases dramatically due to significant reduction in path-loss effect. Moreover, it can be seen that as N increases from 10 to 40, the throughout improves which is due to the increase in the number of decoded bits. However, more increase of N, results in the domination of interference decreasing the throughput. When θ is above 80°, we also notice that the throughput, when $N = 10$, is less than that of when $N = 100$. This is because with these high θ values, the UAV operates at lower altitudes where the path-loss effect is low.

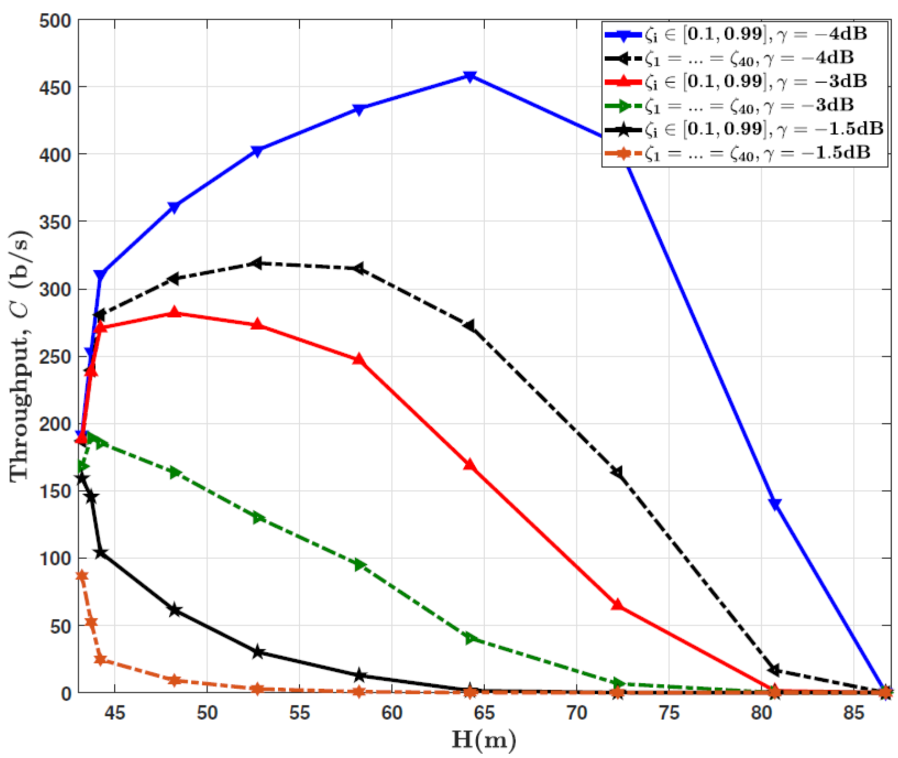

Figure 8 Throughput performance with respect to H.

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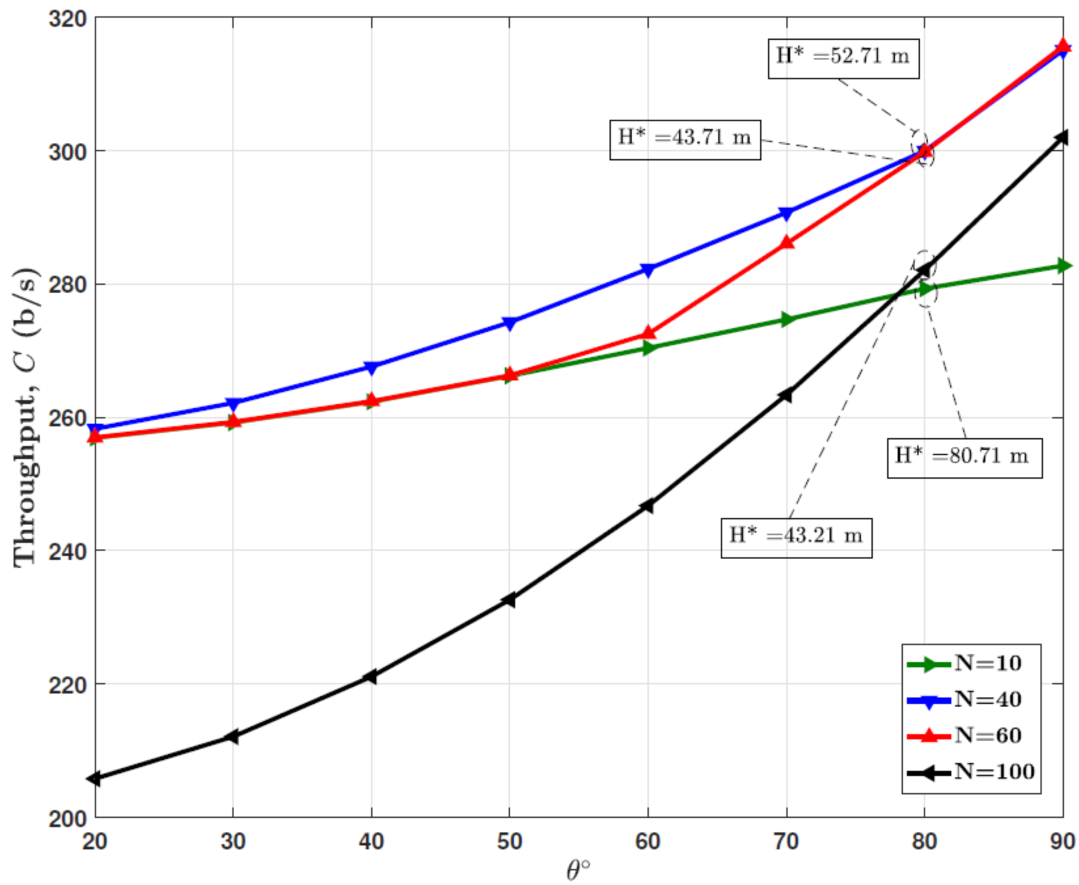

Figure 9 Throughput at optimized altitude with respect to θ.

8 Resources

The work reported in the previous sections is the result of research activities performed by the following researchers. The following table provides the names, dates of secondments and the corresponding person-months.

Table 1: List of researchers involved.

Researcher ID	First Name	Last Name	Sending Organisation	Seconded To	Person-months
32	Petar	Popoyski	AAU		--[1]
20	Anders	Kalor	AAU		--[1]
29	Robert	Heath, Jr	UTA		--[1]
2	Ozgur	Ercetin	SU	--	--[1]
15	Amr	El-Sherif	NU	AAU	1.2
23	Osama	Hanna Habib	NU	AAU	9
9	Osvaldo	Simeone	NJIT	--	--[1]

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22	Amin	Farajzadeh	SU	Carleton	4
17	Mehdi	Heyderabad	SU	Carleton	2
37	Badiaa	Fouad	NU	AAU	3.67

[1] Since there was no secondment under this WP for these researchers, none was reported. Nevertheless, these researchers participated in the research.

9 Publications

The following publications that cover project H2020-MSCA-RISE-2015- TACTILENet-690893 are linked to this deliverable.

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