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Oscar Tonelli*, Ignacio Rodriguez*, Gilberto Berardinelli*, Andrea F. Cattoni*,
Jakob L. Buthler*, Troels B. Sørensen* and Preben Mogensen*§
*Department of Electronic Systems, Aalborg University,
§Nokia Solutions and Networks,
Aalborg, Denmark
ot@es.aau.dk

Abstract— The characteristics of the deployment scenario are fundamental elements in the performance evaluation of wireless networks inter-cell interference coordination (ICIC) schemes. The statistical validation of such concepts is typically achieved by means of system-level simulation campaigns where regular reference scenarios and stochastic channel models are employed. It is an important next step to verify that the trends observed in the reference scenarios compare equally well in more practical deployments. For such comparison, it is required to evaluate an extensive set of link conditions, reflecting the many possible configurations that can be experienced in a practical scenario. In this paper we adopt an experimental procedure, using a software defined radio testbed, for acquiring almost 1000 different radio link conditions between the nodes of a relevant wireless indoor network scenario. The acquired measurements were used as input to a system level simulator for evaluating the performance of a local area decentralized ICIC scheme. The obtained performance results highlight the contribution of the selected scheme and provide a new insight for the validation of the related simulation-based studies, previously published in literature.

Inter Cell Interference Coordination; Dynamic Spectrum Access; Experimental Validation; Indoor Path Loss Modeling

I. INTRODUCTION

Distributed schemes for the inter-cell interference coordination (ICIC) are currently considered for managing the interference problem in contexts of massive small cells deployments in local area scenarios. In particular, ICIC schemes in the frequency domain (FD-ICIC) may employ dynamic spectrum access (DSA) mechanisms for mitigating the interference generated between neighboring cells. The performance gains achieved by ICIC schemes may be very sensitive to the characteristics of the deployment scenario [1]. For local-area environments for example, building-specific propagation and deployment topology play a fundamental role in determining the interference levels experienced by the cells in the network. System level simulators are the preferred tool for large-scale analysis of ICIC schemes, since they enable to easily reproduce a large number of network configurations in reference scenarios. In simulations, regular building configurations and stochastic channel propagation models are typically assumed, aiming for comparable studies. Given the importance of the scenario characteristics in the performance analysis, a comprehensive validation of ICIC concepts should also consider real-world trials, which provide direct information about wireless links in specific network deployments. Exploiting experimental data for increasing the accuracy of the system-level simulation analysis, is a problem previously addressed in literature. In particular, the precise characterization of the performance of the wireless links has been identified as of major importance by several network-oriented studies. In [2] for example, a WiFi testbed is employed to calibrate the wireless model of the ns-2 network simulator: the authors highlight the difficulties in replicating the real-world network topology in simulation, due to limitations of the propagation model. Similarly, in [3] a mesh testbed collects site-specific path loss information for improving the modeling of the network capacity. In [4], experimental data are utilized for the calibration of the ns-3 simulator link models. The cited experimental trials aim at improving the modeling assumptions made in simulations. However, the limited amount of measured links hinders the direct utilization of the experimental data for the validation of a large network in practical deployments.

In this paper we aim at verifying the performance of a decentralized FD-ICIC solution, named Autonomous Component Carrier Selection (ACCS) [5], considering real-world network deployment conditions. The proposed experimental approach relies on the direct utilization of almost 1000 different radio link measurements in an indoor scenario, for the performance evaluation with a system level simulator. The obtained results are then compared with model-based literature studies, in order to obtain further insights on the algorithm performance in site-specific scenarios. The remainder of this paper is organized as it follows: in Section II the contribution of site-specific scenario information in ICIC system-level simulators is discussed; Section III describes the experimental approach adopted for acquiring extensive on-site path loss information. Section IV analyzes the characteristics of the considered network deployment in relation to common simulation scenario models. Section V discusses the ACCS performance in respect to its key configuration parameters and compares the results with prior literature findings. Finally, conclusions are drawn in section VI.

II. HYBRID SIMULATION APPROACH FOR CONCEPT VALIDATION IN REAL-WORLD SCENARIOS

The execution of FD-ICIC schemes is typically part of the radio resource management (RRM). Their performance evaluation requires to analyze a wide range of possible interference conditions over multiple network deployments. System-level simulations are a well-known mean for achieving such analysis, typically relying on reference scenario models. By following the Monte-Carlo approach, a statistical coverage of the propagation characteristics of a given environment can
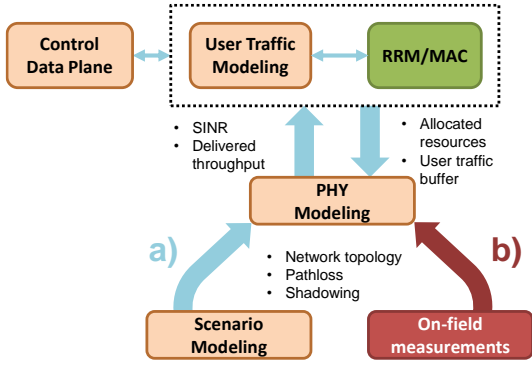
Figure 1. Validation strategy: typical scenario modelling in a system-level simulator (a) is substituted by direct on-field link measurements (b)

be obtained by considering repeated spatially-random deployments of user equipment (UEs) and access points (APs) over multiple simulation snapshots. At each snapshot for example, system processes can be executed and performance results are collected on a per-cell basis. The overall network analysis can be obtained by aggregating individual cells results over multiple simulation snapshots.

A. Modelling assumptions in RRM system-level simulations

System-level simulators focusing on the execution of RRM concepts typically rely on a number of abstractions for modeling the execution of other tasks in the system architecture. In Figure 1 is depicted a scheme of common modelling assumptions made in RRM simulators for the implementation of a generic network node. Resource allocation mechanisms may be executed on a time-frame basis, relying on traffic models for modeling the user data request. ICIC schemes may exploit DSA mechanisms thus implementing decision-making processes which manage the spectrum allocation on the base of spectrum sensing information and channel capacity measurements. These inputs can be provided in simulation by a physical layer (PHY) model which computes Signal-to-Interference-and-Noise Ratio (SINR) estimations on the base of the resource occupation in the network, and wireless link parameters (e.g. path loss, shadowing). Delivered throughput over the links can be obtained by mapping the SINR over the achievable capacity according to technology-specific formulations [6]. The scenario model defines the wireless links characteristics in the network on the base of channel propagation assumptions and deployment topology. Reference channel models for the network analysis in local area environments are, for example, the WINNER II [7] and its derivations in the 3rd Generation Partnership Project (3GPP) HNB [8]. The deployment environment geometry is also part of the specifications included in the scenario model: the ICIC problem in indoor area is usually addressed by referring to regular building configuration with multiple (3x3, 5x5) blocks of contiguous rooms/apartments. Larger scenarios considering the presence of multiple stripes of rooms/apartments divided by corridors or streets are identified both in [7] and [8].

B. System validation under real-world deployment conditions

The adoption of geometrically regular scenarios for the analysis of the interference characteristics of a network

deployment, eases the understanding and comparison of resource allocation schemes in a multi-cellular network. The performance results obtained in this context are however hard to relate to real-world cases where specific signal propagation characteristics may considerably alter the interference scenario and thus the effectiveness of the ICIC algorithms. Acquiring on-field information in relation to a network deployment can provide then the missing input for a more comprehensive concept validation. In this work we devise an experimental approach for exploiting real-world link information in the simulation-based analysis of distributed ICIC solutions. By measuring the path loss characteristics of multiple node locations in a defined environment, it is possible to generate a scenario data-set to be used in "hybrid" system-level simulations to reproduce multiple network deployments, highly representative of real-world configurations. Referring again to Figure 1, the validation strategy consists in substituting reference scenario and propagation models, with direct radio link path loss measurements and related information about nodes topology. From the practical perspective, the main challenge is measuring a sufficiently large amount of radio links, with a testbed, enabling the statistical analysis of node deployments across the considered environment. In the next section the technical details about the developed setup and adopted procedures for the collection of measurements in an indoor scenario are presented.

III. MEASUREMENT CAMPAIGN

Acquiring on-field information about the path loss characteristics of a large-scale network deployment is particularly challenging due to the high number of link measurements involved. In our work we achieve this objective with a testbed of limited size, by assuming static propagation environment conditions and by adopting a measurement procedure which relies on multiple re-locations of the testbed nodes. In order to validate the execution of FD-ICIC concepts for local area, an indoor scenario has been selected as the target for the on-site analysis; the measurements took place at the ground-floor office premises of a building at the Aalborg University campus (NJV12). In order to obtain a sufficiently large pool of locations to be used in the hybrid system-level simulations, 45 positions have been identified across the scenario providing a total of 990 wireless links to be measured. An overview of the defined NJV12 scenario is given in Figure 2. The 45 node locations have been selected as such that at least 3 nodes could be placed over an area of 3x6 meters, and at least 3 positions were covered in every room; this configuration enables to obtain a homogenous sampling of the
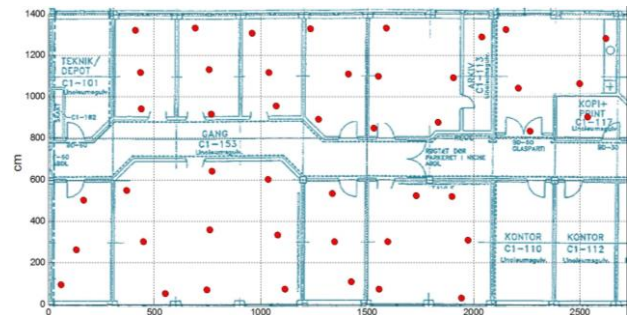

Figure 2. NJV12 Scenario - location of the 45 measured nodes positions

| Antenna Characteristics	Omi-directional, placed at 1.7m height
Tx Signal BW	10 MHz
Tx Power	12.4 dBm
Total RF gain (antenna+cabling)	1dB
Measurement time interval	0.164 sec
Carrier frequency range	4.91 to 5.89 GHz
Frequency step	20 MHz
Number of time/frequency measurements per link	Variable, up to 850 measures for each single link.

Figure 3. Averaged link path loss values measured across the NJV12 scenario in the individuated positions.

Figure 4. SINR at the user for a Reuse1 scheme for different deployment scenario assumptions.

area, supporting the later analysis of multiple network cells which can be physically mapped over the available rooms. Considering a testbed of 14 nodes, a minimum of 19 testbed re-deployments (during which nodes are iteratively re-located over different sets of positions) revealed to be necessary to measure all link combinations. To guarantee static propagation environment conditions throughout the entire experimental session, the measurements were remotely controlled and performed during the time of a single night when the building was empty. By analyzing the large amount of measurements collected, the obtained average link path loss values proved to be insensitive to the impact of multiple testbed re-deployments. The employed testbed setup features the Ettus USRP N200 boards and the XCVR2450 radio-frequency (RF) daughterboards. All system functionalities related to the measurement execution, testbed control and result acquisition, have been developed with the ASGARD SDR software platform [9]. An estimation of the path loss over a wireless link is obtained by measuring the received power of a reference signal transmitted by a node. A single power measurement sample is typically affected by multipath fading and shadowing effects, which vary according to the employed carrier frequency and the propagation characteristics of the environment. Multiple measurements both in time and frequency have been considered for a reliable characterization of the links. All measurements have been performed in the 5 GHz band, averaging in time the samples obtained from a 10 MHz wide reference signal. The effect of multipath fading has been addressed in the frequency domain by repeating the measurements with a carrier frequency varying from 4.91 to 5.89 GHz with steps of 20 MHz. Frequencies from 5.17 to 5.25 GHz have been excluded due to the detected activity of external wireless equipment. In Table I a comprehensive summary of the configuration parameters employed for the measurements is reported.

The obtained link path loss measurements have been included in the scatter plot in Figure 3: line-of-sight (LOS) links (e.g. positions located in the same room) show path loss values ranging from 45 dB to 53 dB with a distance from 2 to 7 meters. High path loss links (distance over 15m) are affected by a saturation effect mainly due to the noise-limited sensitivity of the processing with the USRP hardware. From a topology perspective, these links relate to node locations divided by more than 5 walls.

IV. DEPLOYMENT SCENARIO ANALYSIS

In order to compare the statistical impact of FD-ICIC schemes in network configurations with different
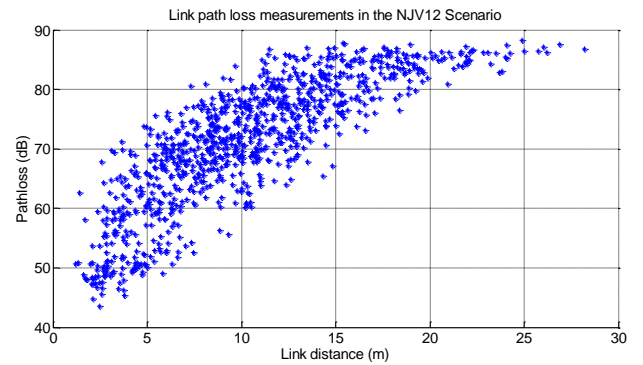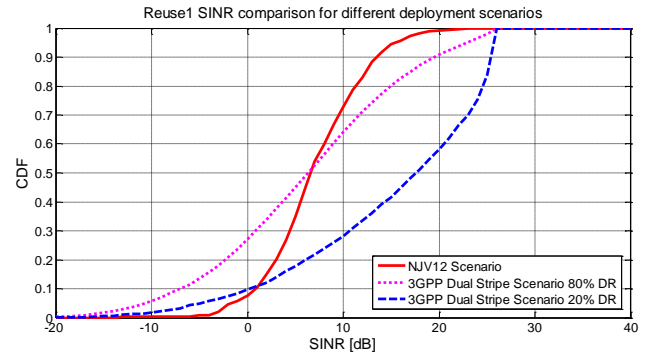
characteristics (e.g. geometry, density) and thus relate simulation scenario models with site-specific deployments, we first estimate the baseline interference conditions given by the topology in terms of experienced SINR at the users assuming a universal frequency reuse scheme (Reuse1). In our study we compare 100 random network layouts in the NJV12 environment (thus exploiting the acquired radio link measurements with hybrid simulations) with an equal amount of deployments in the 3GPP dual stripe simulation scenario model. The dual stripe scenario is particularly relevant for our analysis due to its widespread utilization as a reference for local area ICIC studies in literature. The SINR values relate to downlink transmission only in full load traffic conditions. 10 active cells are concurrently active in the NJV12 environment, while two different deployment ratio (DR) probabilities (20% and 80%) are considered for the multi-floor 3GPP dual stripe model (up to 120 cells may be active). 1 AP and 1 UE are located in each cell according to a closed-subscriber-group (CSG) policy. The cumulative distribution function (CDF) of the estimated SINR for the three considered scenarios is plotted in Figure 4, including all layouts. The NJV12 scenario shows an SINR distribution with a rather narrow range (20 dB); this can be explained with the spatially compact deployment of the cells which instead spans over a considerably larger area in the dual stripe model case. Two major indications can be derived from these results in relation to the network performance:

1) The limited number of total interferers in the NJV12 scenario determines an outage network performance (5-th percentile of the CDF) similar to the sparser dual stripe deployment (20% DR)

Cells/Number of users	10 cells, 1 user per cell
User Affiliation	CSG - User connects to the AP in the room
Total available spectrum	10 MHz
Number of CCs for allocation	Variable
Tx Power	24 dBm
Power per CC	Variable spectral power density according to allocation
Traffic model	Full load
Simulation time per snapshot	100 sec
Error Vector Magnitude	5%

2) Conversely, the best cells in the NJV12 case (95% of the CDF) experience much higher interference levels, due to the lower probability of deploying a completely isolated cell in a smaller environment.

The contribution of FD-ICIC solutions in improving the user capacity is typically higher in high interference conditions. Given comparable useful signal power (AP to UE links) in the three scenarios, relative performance gains are expected to occur in correspondence of lower SINR values shown in the curves of Figure 4.

V. PERFORMANCE VALIDATION OF DECENTRALIZED FD-ICIC SOLUTIONS

In this section we exploit the collected information about the experimental deployment for validating the performance of the Autonomous Component Carrier Selection algorithm (ACCS) [5]. ACCS is a decentralized ICIC solution originally conceived for applications in context of Long Term Evolution Advanced (LTE-A) femtocells, and also considered for standardization by the 3GPP consortium. A number of studies have been published [10], [11] focusing on the ACCS performance in indoor residential/office scenarios. The hybrid simulation results here discussed, allow to compare these prior literature findings obtained in reference scenario models (such as the previously discussed 3GPP dual stripe), with a relevant practical office deployment. The ACCS algorithm enables a distributed allocation of the spectrum resources in a network by relying on sensing information and explicit coordination between the APs (or eNBs according to the 3GPP terminology). ACCS assumes the available spectrum to be divided in a number of chunks named Component Carriers (CCs) which can be dynamically allocated by the APs thus coping with unplanned interference conditions in a multi-cellular context. The ACCS decision-making process is executed periodically on a time-frame basis and relies on the definition of interference thresholds (in terms of SINR and Carrier to Interference ratios) which are typically empirically determined. All results here presented, have been obtained considering 100 random network layouts with similar characteristics to the analysis in Section IV. A summary of the parameters employed in the hybrid simulations, is reported in Table II.

A. Analysis of fundamental configuration parameters

One of the most critical configuration parameters for ICIC schemes assuming fractional spectrum reuse, is the number of spectrum chunks to be utilized. This parameter determines the
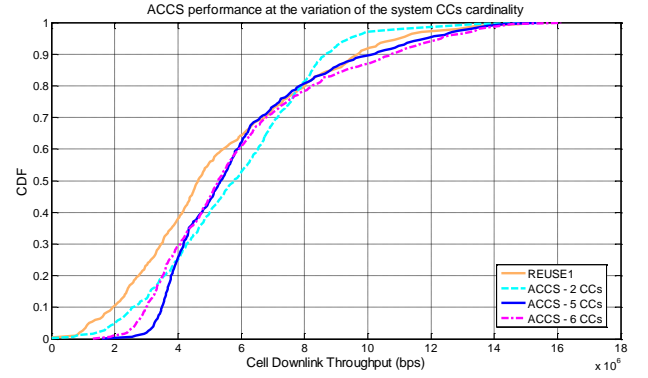

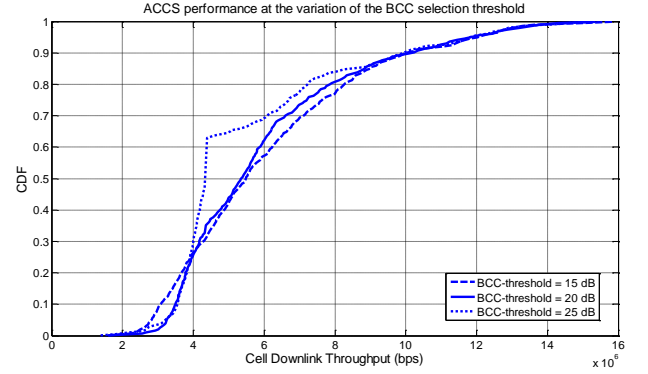Figure 5. ACCS performance in relation to the number of CCs utilized

Figure 6. Evaluation of the ACCS BCC selection threshold

tradeoff benefit between throughput gains in the outage and peak performance: in ACCS this corresponds in defining the cardinality of the CCs. Downlink throughput results for the NJV12 scenario have been generated for different sets of CCS, and reported in Figure 5. Increasing capacity gains are experienced by outage users at the increase of the fractional frequency reuse enabled by additional CCs. Maximum benefit is achieved for 5 CCs; further fractioning of the spectrum does not provide sufficient SINR gains to compensate the reduced transmission bandwidth. The number of 5 CCs has been selected as reference in the literature ACCS studies with the 3GPP double stripe mode [10]: intuitively, 5 is the number of the spatially closest neighbors (1 wall apart, single floor) that a cell may suffer in the worst case considering the geometrical shaping of the double stripe scenario. The same characteristics can be identified in the experimental NJV12 case here considered.

A second aspect in the execution of the ACCS algorithm concerns the tuning of decision-making parameters such as the interference thresholds employed for the allocation of CCs in the network. The original version of the ACCS algorithm aims at enabling maximum protection for the main communication channel between the AP and the users. In the frequency domain this channel is identified with a single CC named Base CC (BCC). The ACCS selection thresholds enable the sharing of CCs between multiple cells, under the constraint of not generating excessive mutual interference. The allocation threshold relating to the sharing of a BCC resource is usually the most conservative, and it then represents a key parameter affecting the frequency reuse in an ACCS-based network.

Optimal thresholds are usually empirically determined. The performance results obtained in the NJV12 scenario and included in Figure 6, show an overall higher capacity gain for a BCC threshold of 20 dB. As a reference, the studies in [10] with the dual stripe model select a lower threshold of 15 dB.

B. Performance results comparison

On the base of the scenario analysis of Section IV, the ACCS results obtained in NJV12, can be directly compared to the findings presented in [10] for the 3GPP dual stripe case. The relevant performance values, related to the downlink cell throughput, are reported in Table III for the cases of Reuse1, ACCS and also a non-parametric version of the algorithm named Generalized-ACCS (G-ACCS) [10]. Values in the table are normalized by the maximum theoretical capacity of the system (corresponding to a value of 100%), thus enabling to cope with the different system bandwidth assumptions in the two studies. In [10] results for 20% and 80% deployment ratio probability are reported. In our analysis we limit the comparison only to the high load user traffic condition. Simulation assumptions in respect to CC cardinality, transmission power and receiver characteristics are set to be fully compliant.

The performance of all reuse schemes in the NJV12 scenario shows comparable values with the 20% DR dual stripe case, in relation to the network outage (worst 5% users): this finding is coherent to the SINR analysis of Section IV where it has been identified that the NJV12 scenario outage interference conditions are closely resembling the experience of a sparse network deployment in the dual stripe model. Average network values and peak performance (95%-tile of the network users) show instead results comparable to a much denser (80% or higher DR) network deployment. Referring again to Figure 4, the high Reuse1 interference conditions in the NJV12 scenario for median and peak users allow to obtain higher gains from the execution of ICIC schemes. The relative gain between ACCS and Reuse 1 in the experimental deployment proved to be consistent with the prior model-based analysis for all network cases. Finally, the distinctions between the ACCS and its generalized version (whose concept details fall beyond the scope of this paper) are also confirmed by comparing the NJV12 scenario and the dual stripe model results.

VI. CONCLUSIONS AND FUTURE WORK

In this paper, the performance of a FD-ICIC solution, namely ACCS, has been validated for an indoor office scenario. The real-world data obtained by an extensive measurement campaign with an experimental testbed have been directly used in a hybrid system-level simulation in order to evaluate the performance of a network deployment configuration under realistic propagation conditions. The results have been compared to reference scenario models with stochastic propagation assumptions, confirming the validity of prior literature studies as representative of a realistic network experience. Relating the performance gains across deployment scenarios with different sizes and densities, requires a careful analysis of the data especially in relation to the 5%-tile and 95%-tile of the network users. As future work, an extension of

TABLE III.   RESULTS COMPARISON SUMMARY

Scheme	Scenario	Outage	Avg	Peak
Reuse 1	NJV12	6.6%	29.7%	60.8%
	Dual Stripe 20% DR*	5%	60%	100%
	Dual Stripe 80% DR*	0.9%	21%	64%
ACCS	NJV12	18%	33.3%	65.8%
	Dual Stripe 20% DR*	19%	66%	100%
	Dual Stripe 80% DR*	12%	30%	59%
G-ACCS	NJV12	15.1%	33.3%	79.4%
	Dual Stripe 20% DR*	17%	70%	100%
	Dual Stripe 80% DR*	6%	32%	72%

* Results extracted from [10].

the real-world validation of ICIC concepts to other scenarios with different propagation and interference characteristics will be considered. Future trials will aim to address, for example, multi-floor and open-space scenarios such as malls and conference halls. A more detailed evaluation of deployments considering multiple users per AP will also be considered, in order to characterize the ICIC algorithm capabilities of dealing with inhomogeneous interference levels within a single cell.

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