DAS, Uncoordinated Femto and Joint Scheduling Systems for In-Building Wireless Solutions

Liu, Zhen; Sørensen, Troels Bundgaard; Wigard, Jeoren; Mogensen, Preben

Published in:
I E E E V T S Vehicular Technology Conference. Proceedings

DOI (link to publication from Publisher):
10.1109/VETECS.2011.5956694

Publication date:
2011

Document Version
Accepted author manuscript, peer reviewed version

DAS, Uncoordinated Femto and Joint Scheduling Systems for In-building Wireless Solutions

Zhen Liu[1], Troels Sørensen[1], Jeroen Wigard[2], Preben Mogensen[1,2]
[1]Aalborg University, [2]Nokia Siemens Networks, Aalborg, Denmark
e-mail: zl@es.aau.dk

Abstract—**Small cells are popular deployment options for coverage holes and capacity hotspot areas. Due to the poor outdoor-to-indoor propagation property of in-building environment, a dedicated wireless system installed inside the building is often preferred for providing indoor users high-data-rate services. Distributed antenna systems and Femto cells are cost-efficient techniques for this application. In this paper, their performance is evaluated in an LTE downlink context along with a proposed joint scheduling system, which maximizes the supported number of users under a QoS constraint. The selection of the enterprise building model includes a general office building model described in the WINNER II project and a site-specific office building with large scale path-loss values retrieved from measurements. Results show superior performance of the Femto system compared to DAS in providing high-data-rate services in most cases with a quality-guaranteed scheduler, while the centralized joint scheduling system gives the best performance. The centralized scheme can also help improve the system robustness in obtaining high performance even in the situation where access points are placed non-optimally.**

I. INTRODUCTION

Nowadays, the rapid growth of high data rate applications has stressed the current macro cellular network infrastructure and facilitated the deployments of small cells. Therefore, Pico and Micro base stations (BS) are deployed in large scale networks at coverage holes and hotspot areas. By decreasing cell size, higher capacity is expected benefiting from massive geometrical reuse of available resources. On the other hand, the majority amount of the mobile traffic is originated from indoor. According to [1], in 2007, more than 50% and 70% of voice calls and data traffic, respectively, are generated by indoor users. However, providing indoor coverage by outdoor sites leads to poor indoor radio quality due to high wall penetration loss. The dedicated in-building wireless system with radio sources emitting inside building is regarded a more efficient approach for providing indoor services. Current in-building wireless solutions include indoor distributed antenna system (DAS) and the envisioned Femto cell systems.

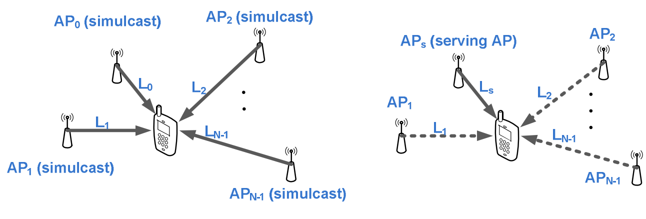
DAS is composed of many remote antenna ports distributed over a large area and connected to a single BS by fiber, coax cable or microwave links. Without advanced signal processing at the central BS, the same downlink signal is broadcasted on all of its antennas, or so called simulcast. Studies show that simulcasting is an effective means to combat shadowing in noise limited environment thanks to transmitter macrodiversity [3]. DAS is first introduced for indoor usage by Saleh [2]. Indoor DAS can help increase coverage and signal-to-noise ratio (SNR) at the same transmission power or achieve power saving and low inter-cell interference. DAS is not implemented in large scale networks, i.e. macro networks, due to high cost, but because of shortened cabling distance and high indoor capacity, literatures argue that DAS is cost-efficient to be used indoor comparing to microcells [3].

Femto is an alternative cost-efficient way to extend indoor coverage and capacity. Femtos are portable, low cost and low range BSs first designated for home usage, where they are deployed by end users and connected to the operator network by residential digital subscriber line (DSL) or cable broadband. With a bit higher Radio Frequency (RF) power and higher supported user number, Femto can be well suited for enterprise offices or campus buildings. In such an environment, due to its low cost, Femto BSs could potentially be deployed with high density, i.e., number of Femto as many as remote antenna ports in DAS. The problem of close-by Femto deployment is the severe inter-cell interference: in user random deployment cases, without any interference management, Femto system performance is significantly degraded [4]. To solve this problem, many studies look for solutions by using soft frequency reuse or flexible spectrum reuse, such as F-ALOHA [5] and ACCS [6]. F-ALOHA is a decentralized interference avoidance algorithm proposes that each Femto cell accesses a random subset of the candidate frequency sub-channels, whereas ACCS takes advantage of exchanged cell load information and measured interference level to dynamically allocate frequency chunks to each cell. In this study, we regard to Femto as uncoordinated Femto with no inter-cell information exchange or interference management. Besides the DAS and uncoordinated Femto systems, we propose a centralized coordinated scheduling scheme which assumes all cells are connected to a central node where cell information is gathered and coordinated resource management could be achieved. Centralized algorithms are also developed addressing the inter-cell interference issue in other studies [7][8], but often with increased implementation complexity and are hardly realized in practice. The algorithm we use is of low complexity, which is expected implementable in real products. It facilitates resource sharing subject to maximizing individual user effective spectral efficiency.

In this paper, we investigate the performance of these systems in an enterprise office building environment in LTE downlink context. Results are generated with WINNER II [9] office building model and channel model, and further verified with a site-specific building model with large scale path-loss values retrieved from real-life measurement [10]. The comparison of different systems is only provided from the radio performance point of view. The purpose is to compare solutions with increasing but practical level of complexity and relevance, based on a fair comparison of radio equipment such as equal number of access points, equal output power per access point, etc. However, other important features such as economical cost analysis and practical implementation considerations have to be included to provide an integrated future enterprise wireless solution vision, which will be the target of our future work.

II. ENTERPRISE SOLUTIONS

In this study, we will compare the radio performance of DAS, un-coordinated Femto and joint scheduling system when serving an enterprise building.



(a) (b)

Figure 1. Multi-AP scenarios

978-1-4244-8331-0/11/$26.00 ©2011 IEEE

The user equipments are situated in an in-building area and surrounded by N in-building access points (AP), as shown in Figure 1. An AP could either be a remote antenna ports in DAS or a Femto BS. We assume the building is covered by a single BS DAS, furthermore, for comparison, we assume DAS and other multicell systems have the same total AP number.

A. DAS

A simulcast DAS with N_{AP} APs is demonstrated in Figure 1(a). Assuming single antenna at both remote AP and user equipment, the distributed multiple simulcasting APs form a macroscopic MISO channel to the user equipment. Without additional preprocessing, the same copies of signal are simultaneously broadcasted by all APs; signal components arriving with different phases at the receiver could add up either constructively or destructively when non-coherent combining is used. This problem can be overcome by transmitter macrodiversity transmission, which gives the best performance in noise limited cases by [11]. However, due to per antenna module power constraints the best transmission strategy maximizing signal to interference-plus-noise ratio (SINR) is phase steering [12], which is adopted in this study.

B. Uncoordinated Femto System

The uncoordinated solution consists of multiple stand-alone APs with no information exchange between them (see Figure 1(b)), and hence is most likely to commit uncoordinated packet scheduling. This is similar to the solution based on Femto BSs that some operators plan to offer for the indoor office environment.

For a multi-cell system with no interference coordination mechanism, referred to as Femto system in the following text, the downlink transmission will suffer from interference from all other active cells operating on the same frequency band.

C. Joint Scheduling System

In the uncoordinated case, for cell edge users who receive strong interference from one or more neighboring cells, their poor SINR condition will either restrict the achievable throughput or lead to costly bandwidth consumption for a quality-guaranteed (QG) service. To provide QG service, a QG scheduler obliges users to achieve their targeted data rate by allocating more resources to users under bad SINR conditions. We use the QG packet scheduling mechanism as the basis to design the coordinated algorithm. A QG scheduling scheme is studied in [14], which allocates each user at least the minimum amount of resource according to user's QG requirement. After satisfies every user's need, if there is spare resources unassigned, those resources will be distributed equally to connected users.

Centralized radio resource management schemes can be designed to improve multi-cell system performance. Under the QG service constraint, our purpose is to design a system that could simultaneously support the maximum number of users. In the LTE downlink context, radio resource is partitioned in both time and frequency domain. The smallest unit of resource a scheduler can operates on in an LTE system is call a resource block (RB), which consists of a set of continuous subcarriers in frequency domain and a subframe of one millisecond in time domain. The long-term average SINR for a certain user i, $\overline{\gamma_i}$, on a RB n considering resource management can be expressed as:

$$\overline{\gamma_i} = \frac{P_{l,n} \cdot G_{i,l}}{\sigma^2 + \sum_{j \neq l} B_{j,n} \cdot P_{j,n} \cdot G_{i,j}} \tag{1}$$

where, $G_{i,l}$ is the long-term channel gain (path loss plus shadow fading) from the i'th user to its serving cell l; $P_{l,n}$ is the allocated power on the n'th RB of cell l; B is a blocking matrix of size $N_{AP} \times N_{RB}$ (N_{RB} is the total number of RBs within one subframe), the entry $B_{l,n} = 1$ means transmission is blocked from transmitting on RB n at cell l to manually turn off severe inter-cell interference, otherwise the entry is set to zero. From the average SINR, given the required minimum user throughput T_{min} and SINR-to-spectral-efficiency mapping function $f_{SE}(\overline{\gamma})$, we can calculate the minimum needed number of RBs per subframe n_i for user i. Then the problem of designing such a system can be formulated as:

$$\begin{aligned} &\max \quad \sum_{l=1}^{N_{AP}} |\Omega_l| \\ &\text{subject to} \quad N_{RB} - \left(\sum_{i \in \Omega_l} n_i + \sum_{n=1}^{N_{RB}} B_{l,n} \right) \geq 0 \quad \text{for } l = 1,2,\ldots,N_{AP} \end{aligned} \tag{2}$$

where Ω_l is the set of users served by AP l.

From the problem stated, the objective is to serve as many users as possible under the given QoS constraint. The problem stated in (2) is generally complex involving serving AP selection, transmitting power control, and RB allocation. A sensible simplification of the problem is therefore to minimize the resource (RB) consumption for each user individually, subject to the constraint. For this purpose we propose the following greedy approach:

1) A RB unaware step one that identifies for each user the (strongest) interferers which should be blocked from transmission to achieve the minimum resource consumption from a per user perspective;

2) A RB aware step two which allocates the required RBs to users, constrained by the blocking in step 1) and with priority to users having the smallest resource consumption. This operation is done jointly for multiple cells, or so called joint scheduling.

As a further simplification, to decouple the AP assignment and transmit power allocation from the resource allocation problem, we further assume that users are assigned to their best server according to minimum path loss and with constant transmit power density (same transmit power per RB). The detailed operation in the two-step greedy approach is introduced in the following section:

1) Step one: strong interfer identification

In order to minimize the RB consumption for each user as stated above, it is equivalent to maximizing the per RB spectral efficiency for each user individually. That is, to find the optimum set of APs whose transmission should be blocked to minimize RB consumption for user i. The problem can be expressed as:

$$x_i = \arg\max_{x'_i \in X_i} \frac{f_{SE}\left(\overline{\gamma_i(x_i')}\right)}{1 + |x_i'|} \tag{3}$$

where X_i is the set of all combinations in the set $\{1,2,\ldots,l-1,l+1,\ldots,N_{AP}\}$, and $|X_i| = 2^{N_{AP}-1}$; x_i^* is the optimal set for user i. This scheme is denoted by 'Co-sch1' in chapter IV.

A further simplified approach for practical implementation to limit the search is to decide the strong interferers based on a fixed threshold γth: each neighboring cell is compared pair-wise with the serving cell AP of their measured average channel gain; one AP will be considered as a strong interferer if the difference is below the predefined threshold. This is shown in the following flow chart.

$$\begin{aligned} &\textit{for} \quad j = 1,2,\ldots,N-1 \\ &\quad \textit{if} \quad G_{j,i} - G_{l,i} < \gamma_{th} \\ &\quad \textit{then}, \text{add } j \text{ to } x_i \\ &\quad \textit{endif} \\ &\textit{end} \end{aligned}$$

This scheme is denoted by 'Co-sch2' in section IV.

2) Step two: RB allocation

In this step, we assign required RBs to users. The operation is done jointly for multiple cells on a RB loop, i.e., each time allocation is done on one set of co-channel RBs of all N_{AP} cells; in the goal of maximizing per RB spectral efficiency under constraint set by step one. We assume the indoor channel is frequency flat, so that interchanging the position of the RBs on the spectrum has no effect on throughput.

For each set of co-channel RBs, we first choose a user k who requires the least number of RBs for transmission, $k=\arg\min_{i=1,2,\dots,N_{UE}}(n_i)$. Then we choose the set of other users z_0 maximizing the final spectral efficiency under the blocking constraint. We define the weighted spectral efficiency μ' of a set of users z as summed expected throughput divided by the total consumed bandwidth taken into account RBs that needs to be blocked (4); and define the actual spectral efficiency μ as summed expected throughput divided by total bandwidth of the RB set, which has a number of N_{AP} RBs (5).

$$\mu'(z)=\frac{\sum_{i\in z} f_{SE}\left(\overline{\gamma_i(x_i)}\right)}{\sum_{i\in z}\left(1+|x_i|\right)},\quad \mu(z)=\frac{\sum_{i\in z} f_{SE}\left(\overline{\gamma_i(x_i)}\right)}{N_{AP}} \qquad (4),(5)$$

The set of users, i.e., $z=z_0\cup\{k\}$, is selected that maximizing the ratio of μ and μ', which can be expressed as:

$$z=\arg\max_{z'=z_0'\cup\{k\}}\frac{\mu(z')}{\mu'(z')} \qquad (6)$$

subject to $l_i\neq l_j$ and $l_i\notin x_j$, if $i\neq j, i\in z, j\in z$

where l_i is the serving AP index for user i.

III. SIMULATION ASSUMPTIONS

In the simulation, the users are uniformly distributed in the building with full buffer traffic. The outage level is set to be 5% and all users require a minimum throughput of 2 Mbps. The parameters for macrocells and other LTE related parameters as well as the sub-carrier modeling in OFDM are the same as stated in [14], the macro interference in the generalized building is modeled as a constant noise floor, which has an average power of -143dBm per Hz. Furthermore, we assume that every cell always utilizing all its available frequency resources (a blocked RB is considered utilized); users are connected to the cell with the minimum path-loss; path-loss is measured free of error; transmit power is constant per RB per AP.

For the SINR-to-spectral-efficiency mapping function $f_{SE}(\overline{\gamma})$, the modified Shannon formula in [13] offers an LTE system-level estimation of achievable spectral efficiency. It provides a simple mapping from user average SINR to spectral efficiency taken system constraint and imperfections into account.

Besides the site-specific building model described in [14], a GBM (generalized building model) is implemented with the same dimension, floor numbers and approximately the same number of rooms per floor, as illustrated in Figure 2. The GBM as well as its path-loss model are adopted from WINNER II indoor office scenario [9], including wall and floor penetration loss, shadow fading, etc.

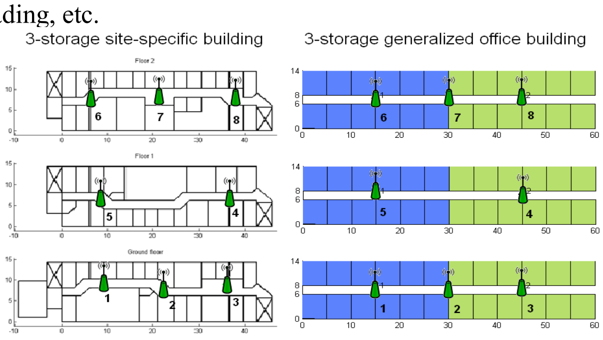


Figure 2. Building Models and AP placement, scales in meters

The placements of APs will also have influence on system performance. Possible locations of APs are shown in Figure 2. The positioning of APs depends on the in-building AP number, see TABLE I. An optional AP placement strategy is that the APs are placed interleaved between different floors, an illustration can be found in [14].

TABLE I. AP locations for different number of APs

In-building AP Number	Location Index
2	4, 5
3	1, 4, 6
4	2, 4, 5, 7
6	1, 3, 4, 5, 6, 8

IV. SYSTEM EVALUATION AND COMPARISON

A. *Capacity estimation with Equal Shared Resources*

The mathematical expression of the user average SNR/SINR distribution in an in-building environment is hard to be written in a closed form due to wall penetration loss. Instead, they are plotted in Figure 3 for DAS and Femtos with interference from macro sites.

The capacity obtained by modified Shannon formula can be written by:

$$C=\frac{N}{R}\cdot B\cdot\min\left\{\int_{\gamma=-\infty}^{\infty}\beta\cdot\log_2\left(1+\frac{\gamma}{\alpha}\right)\cdot p_{SINR}(\gamma)d\gamma,\ \mu_{\max}\right\} \qquad (5)$$

where $p_{sinr}(\gamma)$ is the probability density function of user average SINR γ; B is the system bandwidth; μ_{max} is the maximum system spectral efficiency; $R\in\{1,2\}$ is the hard frequency reuse factor; N is the number of cells, which has the value of 1 in DAS. In a single antenna system with channel-unaware scheduling, α=2, β=0.56 [13]. With 64QAM and 9/10 coding rate being the highest modulation coding scheme, the system capacity for 10MHz bandwidth is shown in Figure 4 (MI denotes for interference from macro sites).

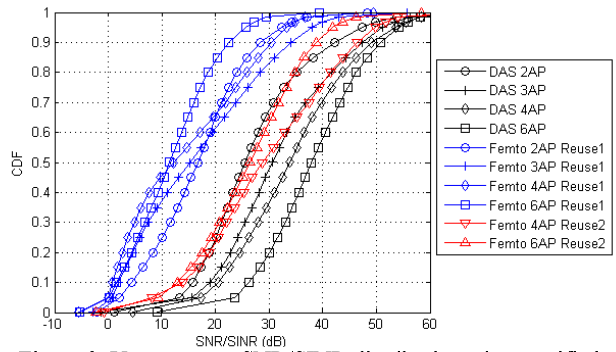
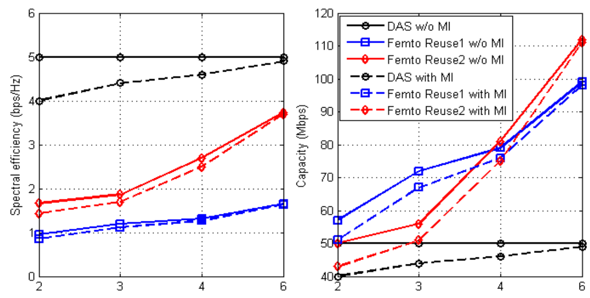


Figure 3. User average SNR/SINR distribution, site-specific building, with macro interference



(a) (b)

Figure 4. Average System capacity of SISO DAS and Femto systems of different AP numbers

Although Femto system gives relatively low average spectral efficiency (Figure 4(a)) due to high inter-cell interference (Figure 3), it achieves higher system capacity (Figure 4(b)) because it increases available resources by reusing resources between cells. DAS performance saturates and is upper-bounded by the single-cell peak data rate of 50Mbps, which is given by $B \cdot \mu_{max}$; system of 6 Femto cells even doubles the overall throughput than DAS with the same number of APs. Macrocell interference deteriorates the system performance; however, this effect is diminished by increasing the number of APs.

B. Simulation Results with QG packet scheduler

In system evaluation, we employ two key performance indicators (KPI):

1. Maximum supported user number subject to the QoS constraint
2. Overall in-building system throughput

The former defines the maximum number of users that can be simultaneous handled by the in-building wireless system, under the constraint that less than 5% of them achieve data rates lower than the predefined minimum target (2Mbps). The two KPIs are denoted by "*UE*" and "*TP*" in following table and figures.

First, the results obtained with the generalized building model will be shown and analyzed. Afterwards it will be verified with a site-specific model. All simulation results are obtained assuming macro interference. Performance of different systems is compared on the same-AP-number basis, and is presented by the percentage gain relative to the performance of Femto reuse 1 system. The reference system performance is presented later in TABLE II. In the following figures, "Femto(R2)" means Femto with hard frequency reuse of factor 2, "Co-Sch1" and "Co-Sch2" represents for the coordinated joint scheduling system with two different schemes described in section II.C.1). The threshold is set to be 10dB in the later scheme.

1) Single antenna at both AP and user equipment (SISO)

The performance gain of different systems compared to the reference case is shown for 2 APs and 4 APs in Figure 5, and 6 APs with two different AP placements in Figure 6.

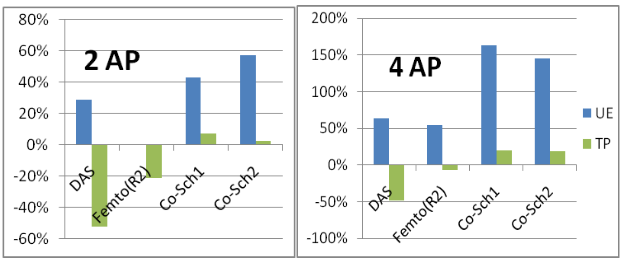


Figure 5. Percentage gain relative to Femto reuse 1 for 2 and 4 APs and SISO transmission

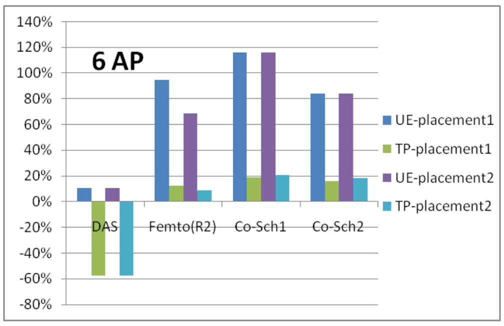


Figure 6. Percentage gain relative to Femto reuse 1 for 6 APs and SISO transmission

The following observations are obtained from the results:

a) Joint sheduling system: it gives the best performance.

b) Femto: with higher number of APs, i.e., more than 2, Femto reuse 2 system outperforms Femto reuse 1 system.

c) DAS: DAS outperforms Femto in the supported user number but offers lower system throughput. Its advantage deminishes by increased number of APs. With 6 APs, Femto with hard frequency reuse of factor 2 outperforms DAS with a big gain in both supported user number and system throughput.

d) Influence of AP placement: the effect of different AP placement is examined for systems with 6 APs in Figure 6. System performance is stable in both placement scenarios for most systems except for Femto with frequency reuse 2. With the optional placement of APs, the performance of Femto in reuse 2 degrades by 13.5% of supported user number and 3% of system throughput. The unstableness of Femto reuse 2 performance can be witnessed also in Figure 8 and Figure 9.

e) The performance advantage of multi-cell Femto system compared to single-cell DAS AP number increases along with the increased number of APs. In TABLE II, the single-cell peak performance represents for the ideal maximum simulcasting DAS capacity. It can be seen that this DAS capacity upper-bound can be surpassed by a Femto reuse 1 system with higher number of APs.

2) Two antennas at each AP and user equipment (MIMO)

Assuming each AP is equipped with two transmitting antennas, and correspondingly two receive antennas are used at the user equipment, the performance of each system with different AP numbers is shown in Figure 7 and Figure 8.

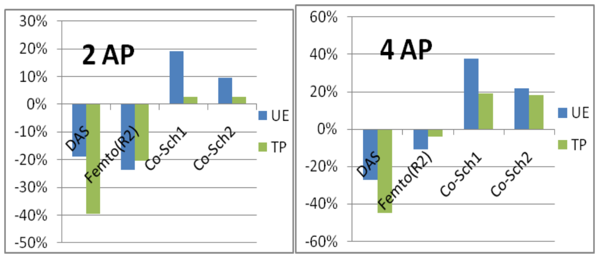


Figure 7. Percentage gain relative to Femto reuse 1 for 2 and 4 APs and MIMO transmission

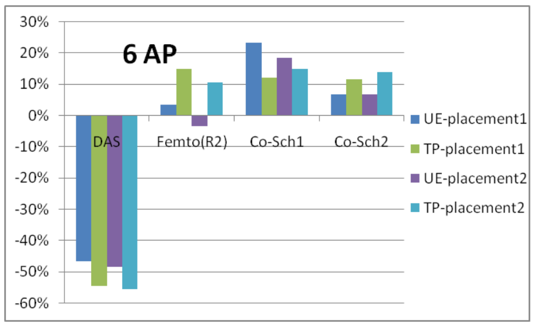


Figure 8. Percentage gain relative to Femto reuse 1 for 6 APs and MIMO transmission

a) Joint sheduling system: Although the gain provided by the joint scheduling system than Femto systems is reduced, it still outperforms the other systems and is robust for different AP placements.

b) Femto: With the help of MIMO techniques, the achievable spectral efficiency of cell edge users in the Femto system can be effectively improved due to diversity combining. Reuse 2 system has no longer absolute advantages comparing to reuse 1 system, which is in contract to the single antenna scenario especially with high number of APs.

c) DAS: DAS with any number of APs performs worse than Femto in both supported number of users and system throughput.

Both reuse 2 Femto and the joint scheduling system improves user SINR by eliminate high neighbor-cell interference. Such systems help user achieve higher spectral efficiency at the cost of losing part of its spectral resource. This scheme is essentially beneficial when improving the SINR from equal-or-less than zero dB to a positive value can significantly increase spectrum efficiency, such as systems with SISO transmission. However, this is less the case for MIMO transmission. With the help of diversity combining, user with low SINR experience significant improvement on achievable spectrum efficiency. The increase on spectral efficiency due to better SINR condition no longer pays off for the lost of spectrum resource for reuse 2 Femto system which starts to perform worse than reuse 1 system. Similarly with the joint scheduling system, in a MIMO configuration, the blocking of interfering APs is shown less efficient in overall performance for many users. In the 'Co-sch1' system, the blockings happen much less frequently with a MIMO setup. Consequently, the performance gain of such a system comparing to Femto reuse 1 system is reduced in MIMO case comparing to SISO case.

TABLE II Reference system performance (Throughput in Mbps)

		SISO		2x2 MIMO	
		UE	TP	UE	TP
Reference system performance	2 APs	7	42	21	73
	4 APs	11	75	37	131
	6 APs	19	105	60	189
Single-cell peak performance		26	50	52	100

The results for the GBM model (above) have similar trend as the results generated with the site-specific building model, as presented in Figure 9 with multi-antenna systems. The notable change is that the Femto reuse 2 system performance is even more sensitive to the AP placement due to the more irregular floor plan, and hence propagation, of this specific building.

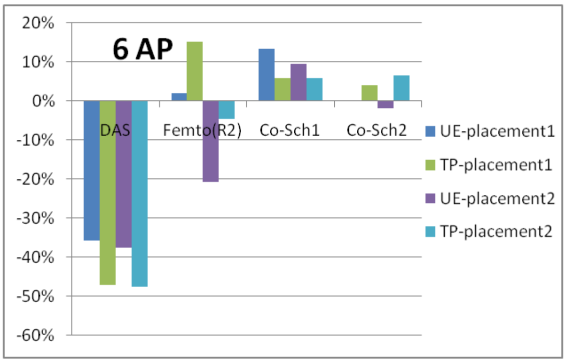


Figure 9. Percentage gain relative to Femto reuse 1 (performance: [UE:53 TP:172Mbps]) for 6 APs with MIMO transmission with site-specific building model

V. CONCLUSIONS

In this study, we evaluate the performance of different in-building wireless systems providing high-data-rate services, including popular solutions such as DAS and Femto cells. A coordinated system is proposed to better exploit the benefits of soft frequency reuse in multi-Femto systems.

In the performance analysis, two office building models are used. Results generated from the generalized building model are verified by those from the site-specific model with accurate large scale channel gain obtained from measurement. We get consistent results between these two models.

From the radio performance point of view, single cell DAS is not suitable for in-building high-data-rate services, because its capacity is restricted by the single-cell peak data rate. It outperforms Femto system on supported user number only at low AP number in the single antenna case. In scenarios otherwise, the Femto system achieves higher overall throughput than DAS, due to that each AP could reuse the whole set of spectrum, and this impact outbalances the SINR deterioration due to high inter-cell interference, and proved to support more users.

High performance of Femto system can be expected at the cost of radio planning, i.e., with good AP placement and with MIMO technology, or resort to the joint scheduling method. Besides providing additional gain, the joint scheduling scheme is proved to help improve the system stability in case of a sub-optimal AP placement. Joint scheduling system can be used to effectively improve the inter-cell interference limited system performance, especially in single antenna systems.

Cost analysis and implementation considerations should also be studied to have a thorough understanding of the practical problems and needs for providing the in-building wireless solutions. This will be our future work. Uplink performance and relationship between performance and building properties (wall and floor penetration, building structure) will also be covered.

REFERENCES

[1] Chandrasekhar, V., Andrews, J., Gatherer, A., "Femtocell networks: a survey," IEEE Commu. Magazine, vol. 46 , no. 9, pp. 59 - 67, 2008

[2] Saleh, A.; Rustako, A.; Roman, R., "Distributed antennas for indoor radio communications," IEEE Trans. Commu, vol. 35, pp.1245-1251, Dec. 1987

[3] Rivas, I., Lopes, L.B.,"Transmitter macrodiversity in radio fibre microcellular networks," IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, PIMRC , vol. 3, pp. 1074 - 1078, 1997.

[4] Villa, Tania, Merz, Ruben, Vidales, Pablo, "Performance evaluation of OFDMA femtocells link-layers in uncontrolled deployments," Wireless Conference (EW), 2010 European, pp. 825 - 832, 2010.

[5] Chandrasekhar, V., Andrews, J.G., "Spectrum allocation in two-tier networks," 42nd Asilomar Conference on Signals, Systems and Computers, pp. 1583 - 1587, 2008.

[6] Luis G. U. Garcia, Klaus I. Pedersen, Preben E. Mogensen, "Autonomous component carrier selection for local area uncoordinated deployment of LTE-advanced," IEEE Vehicular Technology Conference ,VTC 2009 fall

[7] Ju Yeop Kim and Dong-Ho Cho, "A joint power and subchannel allocation scheme maximizing system capacity in dense femtocell downlink systems," IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, PIMRC, 2009

[8] Abrardo, A., Alessio, A., Detti, P., Moretti, M., "Centralized Radio Resource Allocation for OFDMA Cellular Systems," IEEE International Conference on Communications, ICC , pp. 5738 – 5743, Jun. 2007.

[9] IST-WINNER D1.1.2 P. Kyösti, et al., "WINNER II Channel Models," version 1.1, Sep. 2007. Available: https://www.ist-winner.org/WINNER2-Deliverables/D1.1.2v1.1.pdf

[10] Troels B. Sørensen, "Intelligent distributed antenna systems (IDAS), assessment by measurement and simulation," Ph.D. Thesis, Aalborg University, 2003

[11] Jun Zhang, Andrews, J., "Distributed Antenna Systems with Randomness," IEEE Transactions on Wireless Communications, vol. 7, no. 9, pp. 3636 - 3646, 2008.

[12] Wan Choi, Andrews, J.G., "Downlink performance and capacity of distributed antenna systems in a multicell environment," IEEE Transactions on Wireless Communications, vol. 6, no. 1, pp. 69 - 73, 2007.

[13] Preben E. Mogensen and *et al.*, "LTE capacity compared to the Shannon bound," IEEE VTC 2007 Spring, pp. 1234-1238

[14] Zhen liu, et al., "A site-specific study of in-building wireless solutions," IEEE Vehicular Technology Conference ,VTC 2010 spring