System Level Evaluation of Space-Time Turbo Coded MIMO-OFDM for Wide Area Communications

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***Abstract*— It is foreseen that a single (wideband) air interface mode is not sufficient for achieving the high spectral efficiency targets set for next generation wireless system. A dual-bandwidth approach is adapted to simultaneously provide wide coverage and high capacity in a large range of different operating environments. In this paper, hybrid diversity-multiplexing scheme, where Space-time Turbo Coded Modulation (STTuCM) and layered space-time architectures are combined, is used as the air interface for the wide area communication to provide high spectral efficiency and robustness against spatial fading correlation. A system level performance study with different radio resource allocation functionalities applied to the proposed low bandwidth STTuCM orthogonal frequency division multiplexing air interface concept is conducted. The simulation results from the developed system level simulator indicate that the dynamic channel allocation (DCA) results in far better performance than the random allocation, especially in the case of frequency reuse factor one network. Moreover, the single frequency network with DCA performs equally well as the frequency reuse three network with DCA if the frequency resources are limited. Large system level gains can be achieved also if the suppression of structured inter-cell interference is utilized in all terminals. The results also show that transmission modes requiring large number of antennas at both sides of the communication link cannot be supported in the entire simulation scenario even if the frequency reuse of three is used.**

I. INTRODUCTION

Future wireless cellular communication systems are designed to provide high data rates up to 100 Mbits/s for large-area coverage and 1 Gbits/s for indoor or hot-spot coverage. At the same time, the carrier frequencies are expected to grow, e.g., to 5 GHz. This means that the path-loss experienced in the radio channels is also drastically increased. Consequently, building large-area coverage with high data rates becomes expensive, since the cell radii must be limited to be very small causing need for a large number of base transceiver stations.

It is difficult if not impossible to design a common air interface that can simultaneously provide wide coverage and high capacity in a large range of different operating environments, from highly mobile vehicular to quasi-fixed hot-spot scenarios. A dual-bandwidth approach has been recently proposed in [1] to cope with these somewhat conflicting demands. In the proposal, the peak bit rates are provided on a wideband channel, but due to challenges in, e.g., arranging cellular reuse, uplink range, mobile terminal power consumption and scheduling of a wide array of data rates, a narrowband channel format is also proposed.

As the requirement of higher data rates increases, communications systems with very high spectral efficiency need to be developed which rely on multiple antennas at the base station and the terminal. Space-time Turbo Coded Modulation (STTuCM) combines the properties of space-time transmission and turbo coded modulation [2], [3]. When combined with multi-carrier code division multiple access (MC-CDMA) or orthogonal frequency division multiplexing with time division multiple access (OFDM-TDMA) transmission it is especially suitable for high mobility vehicular environments. It has been proven to be robust against implementation impairments, such as channel estimation errors, quantization errors, etc. Hybrid diversity-multiplexing schemes, where STTuCM and layered space-time (LST) architectures are combined, can offer high spectral efficiency and robustness against spatial fading correlation. More details on the physical layer design can be found in [3]. The concept can be very well adapted to different operating scenarios. For example, a low bandwidth option (around 10MHz) can be used for high coverage, while wideband option (around 100MHz) can be used for medium range communication.

Key technologies for future communication systems must eventually be examined in a realistic multi-cell environment similarly to the third generation systems [4]–[6]. The simulation tool developed must support the use of statistical multiple-input multiple-output (MIMO) channel models as well as include also the effects of higher layer functionalities such as radio resource management (RRM) algorithms. In this paper, a system level simulator developed for the proposed low bandwidth STTuCM MIMO-OFDM air interface concept is presented. Moreover, a system level performance study with different RRM functionalities applied to the proposed air interface concept is carried out. A comparison between networks with frequency reuse (FRU) factor value one and three is conducted with different channel allocation methods.

II. SYSTEM MODEL

Dynamic system level simulator is required for studying the system level performance of different future air interfaces while including the effects of higher layer functionalities such as RRM algorithms. Realistic traffic models and terminal mobility must be also implemented. By using the simulator new RRM algorithms developed for future air interfaces can be tested and verified. Similarly to [4], in the developed dynamic system-level multi-cell simulator the physical layer is modelled with look-up tables generated off-line with link level simulations.

The main features of the simulator are the following: generation of common multi-cell simulation scenario, user distributions within the simulation area, propagation loss calculation, generation of correlated large scale fading (shadowing), generation of MIMO channel coefficients for all users and interference sources, multiple access, terminal mobility, traffic modelling, link-to-system level interface, RRM features: adaptive modulation and coding, retransmission schemes, power control, handover algorithms, packet scheduling, dynamic frequency/channel assignment, admission/load control, etc. The model is built in Matlab environment with computationally the most time-critical parts implemented in C++.

57-cell scenario (21 3-sector sites) is used for the multi-cell evaluation. Modified Okumura-Hata propagation model is used for modelling the path loss. The model was originally measured for 2 GHz, thus, a coarse approximation of the path loss for 5 GHz is obtained by adding extra 10 dB attenuation. The effect of realistic 3D antenna patterns is included in the path loss calculations. Fig. 1 shows a multi-cell scenario with 57 sectorized cells with 120° antennas and with -15° antenna tilt. In this figure, the maximum signal level per pixel is plotted. The darker the color the lower is the signal level. In addition to the path loss the signal suffers from the shadowing caused by large obstacles usually around the mobile. The shadowing factor is a log-normal Gaussian variable with mean of 0 dB and the variance of 6 dB.

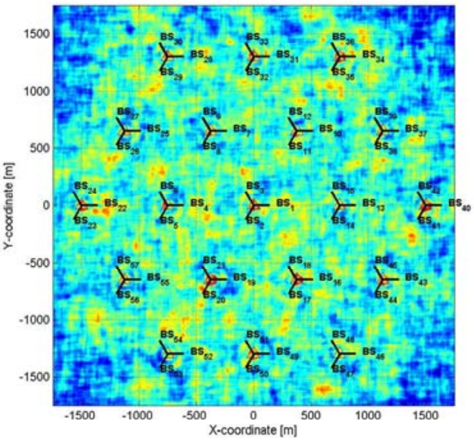

Fig. 1. A multi-cell scenario with 57 sectorized cells with 120° antennas and with -15° antenna tilt, shadowing variance 6 dB

Independent fast fading process is simulated for each MIMO antenna transmitter-receiver pair (both the desired link $\mathbf{H}_k$ and the most dominant interference links $\mathbf{H}_{k,i}$) at each time instant t for each terminal k dropped in the system. Modelling the spatial and time/frequency selective characteristics of all interfering sectors can be prohibitively complex. The solution used is to model only a number of strongest interfering cells as correlated processes while the remaining interferers are modelled as spatially white Gaussian noise processes, variances based on a flat Rayleigh fading process. The channel coefficients are generated by a standardized geometric stochastic channel model (3GPP/3GPP2 spatial channel model [7]).

TABLE I

MAIN SIMULATION PARAMETERS

Channel bandwidth (BW)	12.8MHz
Transmit power	37dBm
Nr of sub-carriers (N)	128
Cyclic prefix (CP)	32
OFDM symbols per TDD frame (N_S)	52(DL) + 52(UL) + 24(Common) = 128
TDD Frame length	$(N+CP)/BW * N_S \simeq$1.6 ms

The simulation run consist of D drops where K users are randomly dropped within the geographic area of the system for each drop. In order to speed up the simulation time only the center site users' data is recorded for the statistics. L frames are simulated for each center cite user during each drop. Large scale mobility is not modelled, but the fast fading is simulated for the stationary users during a drop. The frame structure used in the simulations is very similar to the HIPERLAN/2 structure. The main simulator parameters are listed in Table I.

III. LINK-TO-SYSTEM LEVEL INTERFACE

Due to the processing power constraints it is practically impossible to implement a large multi-cell network with a relatively high number of terminals where all the radio links between terminals and base stations are modelled in link-level. Therefore, a look-up table based approach has been traditionally used to overcome the complexity barrier [4]. Look-up tables, the simulated link level performance vs. a metric reflecting the performance of the studied system at any instantaneous channel realization, are generated off-line from link level simulations.

During the system level simulation a metric value is derived for each instantaneous MIMO channel realization. The look-up table is consulted for each data block to map the generated metric to, for example, an equivalent frame error probability (FEP) value (for some specific modulation and coding scheme) or to a throughput or spectral efficiency value (for FEP fixed). During the data transmission a random experiment is done for each received block/frame in order to define whether the transmission was erroneous or not, i.e., FrameError: $rand[0,1] < FEP(Metric, configuration)$.

An information theoretic metric proposed in [8] is adapted for the link-to-system level interface. It was shown in [8] that such a metric can encapsulate the performance of the receiver, for example in terms of the probability of block error, given the prevailing radio environment over the block duration.

The metric is defined below for a multi-carrier transmission system with N_C sub-carriers, N_T transmit antennnas, N_R receive antennas and for the case the channel state information (CSI) is not known at the transmitter. From the channel model described in the previous subsection the capacity metric C_{metric} for such a case can be written as [8]

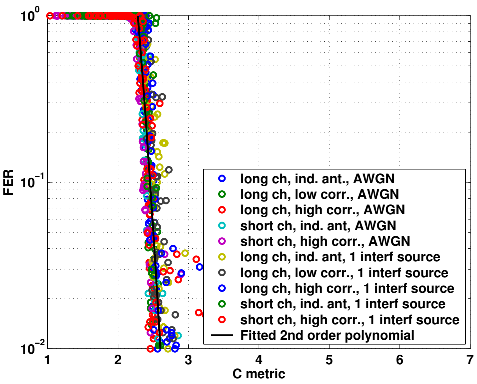

Fig. 2. 2×2 STTuCM MIMO-OFDM, with different channel profiles, spatial correlation, and interference scenarios

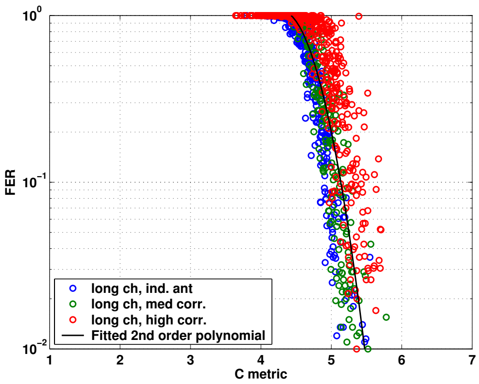

Fig. 3. 4×4 STTuCM MIMO-OFDM with 4 BLAST iterations at the receiver, with different channel profiles and spatial correlation, AWGN interference

$$C_{metric} = \frac{1}{N_C}\sum_{c=1}^{N_C}\log_2\det\left(\frac{\mathbf{R}_{ss}^{(c)}+\mathbf{R}_{ii}^{(c)}}{\mathbf{R}_{ii}^{(c)}}\right) \tag{1}$$

where the signal and interference sample covariance matrices are defined as

$$\mathbf{R}_{ss}^{(c)} = \frac{E_b}{N_T}\left(\mathbf{H}_c\mathbf{H}_c^{\mathrm{H}}\right) \tag{2}$$

$$\mathbf{R}_c = \sum_{i=1}^{K}\frac{E_{b,i}}{N_{T,i}}\left(\mathbf{H}_{c,i}\mathbf{H}_{c,i}^{\mathrm{H}}\right) + N_0\mathbf{I} \tag{3}$$

and, where $\mathbf{H}_c$ is the $N_T \times N_R$ channel matrix for the desired link, and $\mathbf{H}_{c,i}$ represents the $N_{T,i} \times N_R$ channel matrix for the ith interference source of total K interference sources. E_b represents the bit energy and the background noise is modelled as additive white Gaussian noise having the covariance matrix $N_0\mathbf{I}$. Then, (1) can be written as

$$C_{metric} = \frac{1}{N_C}\sum_{c=1}^{N_C}\log_2\det\left(\mathbf{I}_c + \frac{E_b}{N_T}\mathbf{H}_c\mathbf{H}_c^{\mathrm{H}}\mathbf{R}_c{}^{-1}\right) \tag{4}$$

In Fig. 2, the frame error rate (FER) versus information theoretic metric for fixed QPSK modulation is shown for the STTuCM MIMO-OFDM concept with 2×2 antenna configuration and with different channel profiles, spatial correlation and interference scenarios. The plot is obtained by simulating 200 channel realizations (data blocks) for different values of signal-to-noise ratio. The interference is modelled either as AWGN or as one dominant structured inter-cell interference source. LMMSE filter is applied at the receiver to suppress the effect of inter-cell interference.

It can be seen from the figure that the selected metric results in very good fit between the link level results and the system level metric. The link-to-system level interface can be approximated by fitting 2^{nd} order polynomial to the simulated points as shown in Fig. 2. An interesting result related to the STTuCM coding performance can be also noted. The Shannon limit for the simulated case with spectral efficiency of 2 bits/Hz/s would be a straight vertical line at 2 bit x-axis value. Thus, the scheme is able to work at 0.6 bit distance from the Shannon limit at 1% FER.

For the case with higher number of antennas (4×4), the fit between the metric and the link level FER is not quite as good as for low number of antennas (2×2). In Fig. 3 the FER versus information theoretic metric is shown for the STTuCM MIMO-OFDM concept with 4×4 antenna configuration and with different channel profiles and spatial correlation. It can be seen from the figur e that if the spatial correlation is high the transmitter-receiver is not able to exploit the available capacity as efficiently as in the case of non-correlated antennas. Thus, the dispersion is increased and, in general, the average curve is shifted for the spatially correlated case.

IV. SIMULATION RESULTS

A. 2×2 MIMO-OFDM-TDMA system

Dynamic channel allocation (DCA) in time and/or frequency domain can be used to improve the spectral efficiency of the system. DCA is fundamental feature in cellular environments to move towards frequency reuse factor one networks. The users can be allocated to time slots and/or frequencies where the signal level is sufficient for operation (1-way check) and where the new allocation does not interfere too much the existing users (2-way check). DCA requires fully synchronized network and information sharing (allocation tables) between base stations to function properly. Some system level simulation results for the proposed wide area concept (STTuCM OFDM-TDMA) with random allocation and with DCA are shown for 2×2 antenna configuration.

Inter-cell interference suppression by linear minimum mean squared error (LMMSE) filter is assumed at each user terminal. A fixed bit rate real-time (RT) service with guaranteed BW per users is assumed. Each RT user occupies four OFDM symbols per one transmitted DL TDD MAC frame. Other simulation parameters are shown in Table I. A comparison between frequency reuse (FRU) factor value one and three is conducted with random and dynamic channel allocation methods. Also, a very simple frequency reuse one ”timeslot reuse” method is simulated. In this method, labelled as ’TSLreuse3’, the

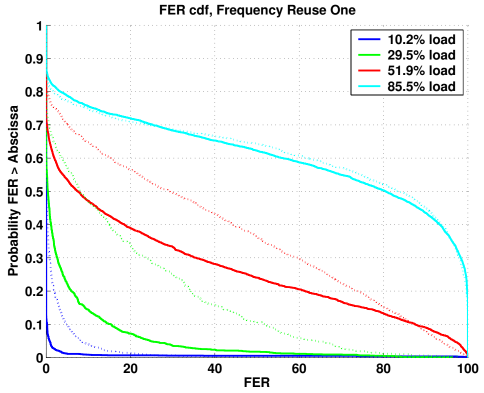

Fig. 4. Cumulative distribution function of FER for different hardware loads, FRU 1, DCA (solid) vs. random channel allocation (dotted)

cells are divided into three groups, each starting the resource allocation from different ends of the allocation table (left, centre, right). The simulated DCA method is rather simple and sub-optimal 1-way DCA in which the users are allocated cell-by-cell to time slots where the resulting SINR is the highest. Obviously, the users in the last allocated cells get always the worst SINR due to the interference from the earlier allocated base stations. In order to preserve fairness, the allocation order between base stations and users was randomly varied between simulated DL TDD MAC frames. Optimal allocation resulting the lowest FER would require exhaustive search over all possible combinations of user allocations in different cells.

Fig. 4 shows the cumulative distribution function of average user FER with different hardware (HW) load values for frequency reuse factor one and for random (dotted line) and dynamic (solid line) channel allocation. The HW load is defined as the average utilization rate of the DL OFDM symbols in TDD frames. The results show that the DCA improves the user FER at low and medium HW loads while the gain is non-existent at high loads. This is due to the fact that the DCA algorithm is able to distribute the empty slots in the allocation table so that the interference between users is minimized resulting lower FER than in the random case.

Fig. 5 shows the percentage of satisfied users (average $FER < 5\%$) as a function of hardware load for different allocation methods. The DCA results in far better performance than the random allocation, especially in the case of frequency reuse factor one. In Fig. 6, the performance is depicted as a function of normalized load, i.e., the HW load is divided by the number of frequencies (one or three). This illustrates the case where the number of frequencies is limited while there is no hardware resource limitation. This is well justified approach to compare the scenarios as the frequency resources can be very scarce. The results show that the single frequency network with DCA performs equally well as the frequency reuse three network with DCA. Moreover, the single frequency network can be loaded much further than the high reuse network, obviously at the cost of decreased quality. Fig. 7 shows the map of the simulation scenario for 50% HW load with DCA and for frequency reuse one. User coordinates are colored by color code corresponding to a specific average frame error rate.

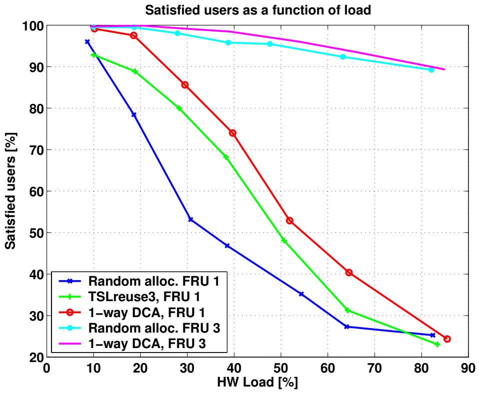

Fig. 5. Satisfied users ($FER < 5\%$) as a function of hardware load, frequency reuse one vs. three

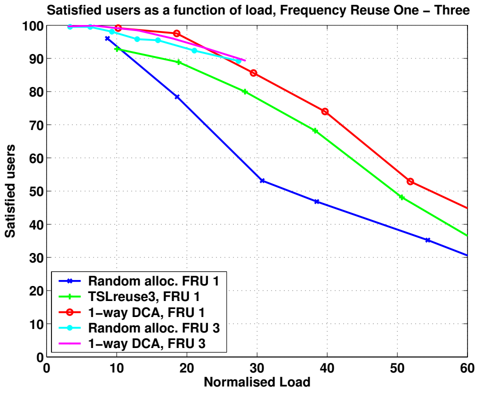

Fig. 6. Satisfied users ($FER < 5\%$) as a function of normalized frequency load, frequency reuse one vs. three

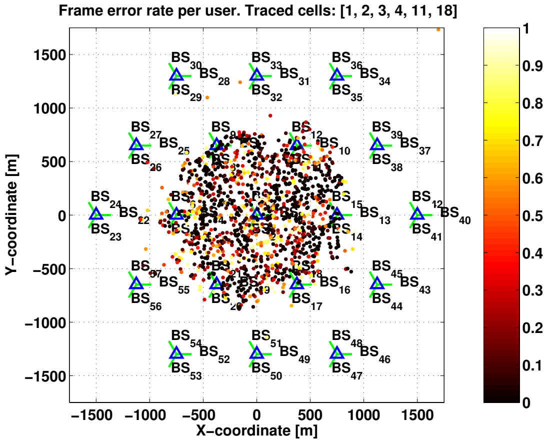

Fig. 7. Average frame error rate per user in the simulation scenario. HW load $\sim 50\%$, frequency reuse one, DCA

B. 4×4 *MIMO-OFDM-TDMA system*

The results for 4×4 antenna configuration with hybrid STTuCM and LST transmission [3], [9] are presented in

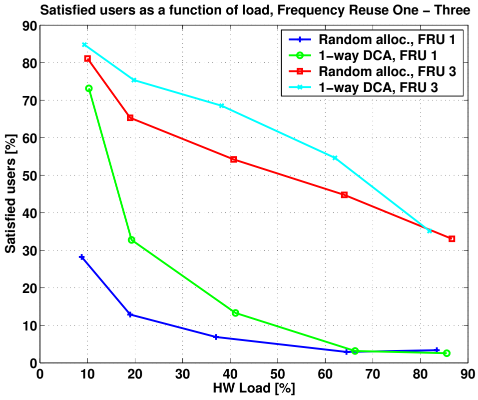

Fig. 8. 4×4 scenario. Satisfied users ($FER < 5\%$) as a function of hardware load, frequency reuse one vs. three

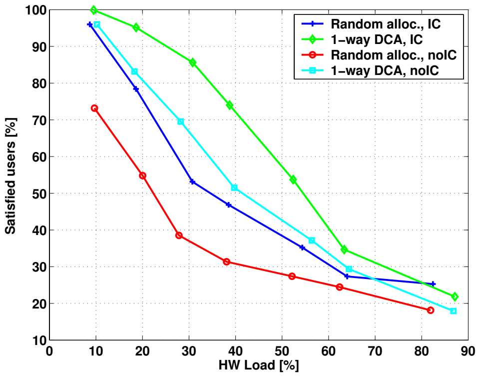

Fig. 9. 2×2 scenario with and without interference suppression at the receiver. Satisfied users ($FER < 5\%$) as a function of hardware load, frequency reuse one

this section. The spectral efficiency of the transmission was doubled from the 2×2 case to 4 bits/Hz/s, and thus, the guaranteed BW per user for simulated real-time service was also doubled. Other simulation parameters are the same as in the previous section. The simulation results in Fig. 8 indicate that the simulated RT service 4×4 with STTuCM transmission cannot be supported in the entire simulation scenario even if the frequency reuse of three was used. Link adaptation and antenna reconfigurability features are required to adapt the modulation and coding scheme and the MIMO antenna structure to different radio conditions.

C. Impact of Interference Suppression at the Terminal

The impact of inter-cell interference suppression at the terminal on the system level performance is studied. LMMSE structure is applied at the receiver to suppress the effect of structured interference. The two cases compared in the simulations are labelled as 'IC' where the interference structure is taken into account in the receiver, and 'noIC' where the interference is treated as AWGN. The simulations results in Fig. 9 clearly indicate that large system level gains can be achieved if the suppression of structured inter-cell interference is utilized in all terminals.

V. CONCLUSION

In this paper, hybrid diversity-multiplexing scheme, where Space-time Turbo Coded Modulation STTuCM and layered space-time architectures are combined, is used as the air interface for the wide area communication mode to provide high spectral efficiency and robustness against spatial fading correlation. A system level simulator is developed for the proposed low bandwidth STTuCM MIMO-OFDM air interface concept. Moreover, a system level performance study with different radio resource allocation functionalities applied to the proposed air interface concept is conducted.

The simulation results indicate that the dynamic channel allocation results in far better performance than the random allocation, especially in the case of frequency reuse one network. Moreover, the single frequency network with DCA performs equally well as the frequency reuse three network with DCA. Large system level gains can be achieved also if the suppression of structured inter-cell interference is utilized in all terminals. The results also show that transmission modes requiring large number of antennas at both sides of the communication link cannot be supported in the entire simulation scenario even if the frequency reuse of three was used. Link adaptation and antenna reconfigurability features are required to adapt the modulation and coding scheme and the MIMO antenna structure to different radio conditions.

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