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Propagation Characteristics, Metrics, and Statistics for Virtual MIMO Performance in a Measured Outdoor Cell

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Abstract—Distributing the construction of a multiple-input multiple-output (MIMO) system among more than one mobile user reduces hardware and processing complexity at the terminal end, and may result in improved channel propagation conditions, particularly those related to spatial correlation. In this paper, measured outdoor propagation data is used to study a 4×4 virtual MIMO system formed from a two-user 4×4 classical system using only two of the antennas at each constituent user. The capacity, K -factor, and spatial correlation are evaluated for 226 possible pairs of users whose channels were measured while standing and walking. The proportions of pairings that result in a capacity increase and K -factor and correlation reductions over both, only one and neither of the constituents are determined. It is found that correlation reduction appears to be a stronger sign of capacity improvement than is K -factor reduction. When choosing a partner for a given single user, results show that it is easier to improve these three parameters as the user's value of them becomes poorer, so thresholds applicable to this data set are found which specify values of capacity, K , and correlation beyond which at least 50% of possible pairings improve matters.

Index Terms— K -factor, capacity, correlation, virtual MIMO.

I. INTRODUCTION

ALTHOUGH the advantages of multiple-input multiple-output (MIMO) systems are now widely appreciated, it remains the case that deploying them in real-world situations faces challenges well known to both theory and practice. In particular, it is attractive to provide as many antennas as possible at both ends of the link to exploit both the diversity and spatial multiplexing (SM) capabilities of MIMO [1], [2]. However, the complexity required to achieve this is particularly limiting at the mobile user in terms of both physical space for antennas and driving multiple radio-frequency (RF) chains [3]. Even if the requirements of the antennas and associated hardware are met, the spectre of spatial correlation may well appear on naturally compact mobile devices, with consequent degradation to SM capability in particular [4], [5]. Since correlation is generally improved by wider antenna spacing, means of imposing a limit on the number of antennas at the mobile are found, for

example via antenna selection schemes [3], [6]–[8] or an outright cap on the number of physical antennas being carried, as is implicitly the case in early commercial MIMO systems such as IEEE 802.11n, which is restricted to four antennas [9].

An alternative approach is to use a much wider-area MIMO system by allowing multiple users to cooperate and form a virtual array using antennas on each of the users [10] to construct a higher-order MIMO system. In this way, the complexity at each user can be reduced and spatial correlation should fall since at least certain subsets of the antennas are significantly further apart than would otherwise be the case. Such “virtual” MIMO schemes are a topic of much current research, with interest from the information-theoretic, e.g., [11] and system algorithm, e.g., [12], [13] points-of-view, and in some specific applications such as wireless sensor networks, e.g., [14], [15]. Virtual MIMO is also incorporated into some wireless standards, such as IEEE 802.16e [16], [17] and 3GPP-LTE [18]. Previous work on the modeling and propagation characteristics of virtual MIMO channels includes the inter-basestation cooperation measurements of capacity reported in [19] and the comparison of several constituent SISO links to their MIMO equivalent in the military UHF band in [20] which highlights some meaningful capacity advantages. A real-time demonstration of the concept of relaying video streams via virtual MIMO (not precisely the system scenario considered here) is documented in [21], showing that the concept can work in practice.

In this paper, a virtual 4×4 MIMO system is formed from two constituent 4×4 users who each activate only two of their antennas. The link considered here is the one from the base to the two cooperating users, which must stand in for the higher-order individual MIMO links it is replacing. The radio channel data was collected in Bristol city-center, UK, in a scenario representing an urban outdoor cell. A user with the mobile unit (MU), in this case a prototype MIMO-enabled laptop, was either standing or walking in a number of physically near-by locations and the base fixed in place with a good view of the city-center (see Section II for full details). The system thus has a geometry and propagation characteristics which are a realistic representation of scenarios in which virtual MIMO is likely to be of greatest interest. The channel data used here comprises a total of 20 standing and 9 walking measurements, from which cooperating pairs are chosen to form virtual MIMO systems.

The analysis in this paper offers four main contributions:

- Typical capacity, K -factor, and spatial correlation values achieved by the virtual system, and a comparison to their values in the constituent classical MIMO users.

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- A determination of the proportions of possible pairings that lead to capacity, K -factor, and spatial correlation improvements for the virtual system over both, either and neither of the constituent users. This is far from all the possibilities, demonstrating that metrics for when virtual MIMO is likely to be useful are valuable.
- The distribution of capacity, K -factor, and correlation vs. how many possible virtual MIMO partners for a given user would improve their value over the classical case.
- Threshold values beyond which at least 50% of possible pairs will lead to an improvement. Any other such percentage could also be assigned a threshold. Although specific to this data set, this does allow similar environments to be characterized for their suitability for virtual MIMO and provides a methodological framework for such analysis with other measurements and also with existing models.

It is important to stress that these statistics and metrics are taken from measured data in an outdoor environment with a geometry chosen for its representation of a likely virtual MIMO scenario and captured with realistic prototype MIMO devices held and mobilized by humans. The contributions identified above are targeted at providing a statistical characterization of when a system operating in a given locality may usefully deploy virtual MIMO versus when it should not. This is in contrast to most previous analytical and modeling work which implicitly assumes that virtual MIMO will be suitable for the environment it is deployed in.

In what follows, Section II summarizes the key features of the measurement campaign and Section III sets out the methods used to construct the virtual MIMO systems and calculate the parameters used in the comparisons. Section IV contains the results that are the key contribution of the paper, and Section V draws conclusions and suggests future work.

II. MIMO PROPAGATION MEASUREMENT CAMPAIGN

Full details of the campaign have been reported previously [22], [23], with the key points summarized here.

A. Measurement Campaign

An extensive outdoor MIMO measurement campaign was carried out around Bristol city-center, using a Medav channel sounder [24]. The measurements were conducted at a center frequency of 2 GHz, with a 20 MHz signal bandwidth. The periodic transmit signal is carried through 128 discrete frequency fingers, and has a repetition period of 6.4 μ s. A 4×4 MIMO configuration was used throughout the measurements. Each measurement lasted for 6 s, in which there were 4096 snapshots of each frequency finger. To improve the measured signal-to-noise ratio (SNR), consecutive sets of 4 snapshots were averaged, taking advantage of the zero-mean white noise statistics. There are thus 1024 time snapshots at each of the 128 frequency fingers.

Measurements were conducted at a total of 56 locations around Bristol city-center, UK, in the four areas shown in Fig. 1. In this paper, the results collected in Queen Square (circled) are used. At each location, 6 s of measurements with each of the three devices described in Section II-B were collected whilst the mobile user was standing facing in each

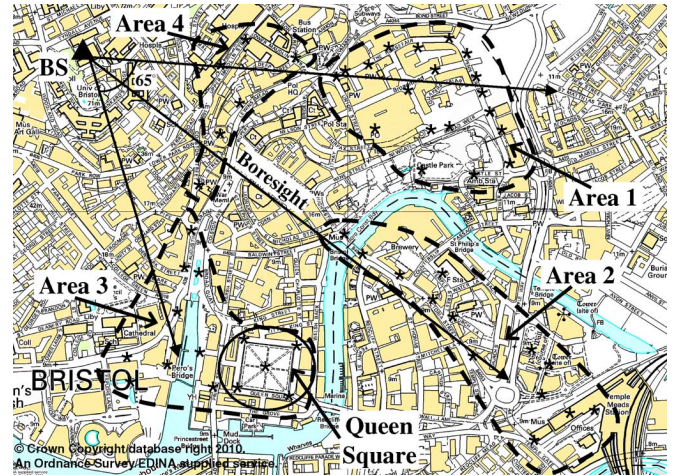


Fig. 1. Map of Bristol city-center, UK, showing measurement locations. Scale is 1:5500. Queen Square is approximately 150 m², marked in Area 3.

of four directions separated by successive approximate 90° rotations, followed by the user walking at 1 m/s for 6 s in each of two approximately perpendicular directions. In Queen Square, there were five locations: one at each corner of the approximately 150 m² square and one at its center. These collections of standing and walking measurements are here taken to represent numerous different possible users whose antennas can be aggregated as desired to form a virtual MIMO system, as described in Section III-D.

B. Prototype Device and Antennas

The measurement campaign was conducted with three different devices: a laptop, a personal digital assistant (PDA), and some head-mounted “reference” dipoles. This paper uses the data collected with the laptop, so all mobile users have equivalent devices. The prototype laptop contained four printed inverted-F antennas (PIFAs) fitted inside the two upper edges of the back of the display panel, as shown in Fig. 2. The co-polar and cross-polar radiation patterns were capable of capturing roughly equal amounts of power from the vertical and horizontal polarizations. On average, 58.6% of the total power was radiated (or absorbed) in the co-polar mode [22].

The basestation (BS) antennas were two $\pm 45^\circ$ dual polarized UMTS antennas (a total of four transmit chains) mounted atop a 30 m high five-storey building overlooking the city center where the measurements were conducted. The antennas were fitted to metal railings, and given 3 m horizontal separation and an 8° downtilt to improve coverage.

III. ANALYSIS METHODOLOGY

The scenario considered in this paper is that there are two users in a locality from among the antennas on which a 2-user virtual 4×4 MIMO system will be assembled. As described above, all the MIMO measurements are 4×4 , so two antennas per user must be selected. Since one goal of virtual MIMO is to benefit from the low correlation between physically separated users, here the two most widely spaced antennas on the device are chosen. In the measured data, these correspond to receive ports 1 and 4, as shown in Fig. 3. These two columns of the

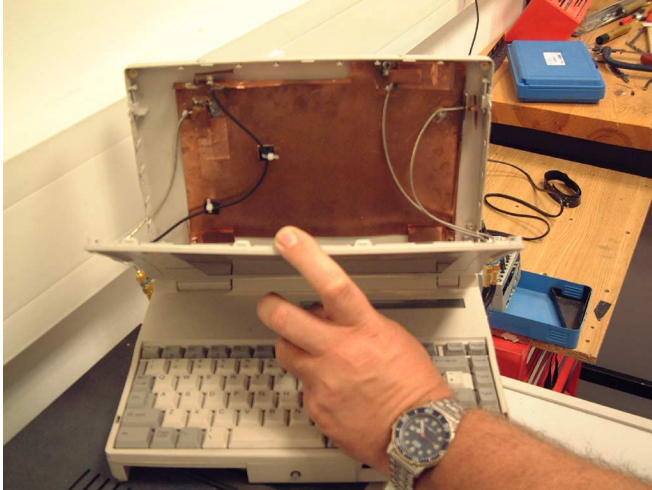


Fig. 2. Customized laptop with 4-element PIFA array.

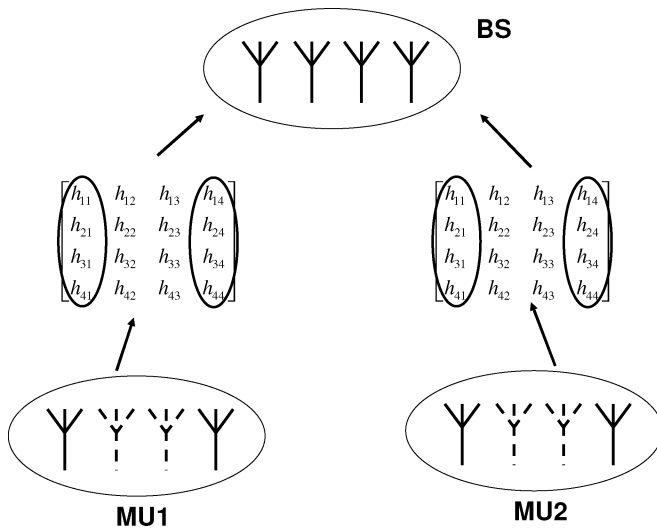


Fig. 3. Construction of virtual 4×4 MIMO system from constituent users.

constituent channel matrices are aggregated into a new virtual MIMO channel whose properties are then analyzed. The comparisons in what follows are principally to the two underlying classical 4×4 MIMO systems from which the virtual 4×4 system is assembled.

Three key parameters to characterize MIMO performance will be studied: information theoretic capacity, K -factor, and spatial correlation. The calculation methods for these are briefly summarized next. The same methods have been used for both the physical and virtual MIMO channels.

A. Capacity

The information capacity is computed using path-loss normalized channels so that a range of system SNRs can be studied easily and independently of the received SNR. The channels are normalized in the time-domain such that they have unit average gain over the bandwidth and all transmit-receive links. In effect, then, power control for virtual MIMO is assumed. Future work studying an un-normalized system could consider the comparison of the virtual MIMO system to constituent systems with a

significant power imbalance, such as between one line-of-sight (LOS) and one non-LOS (NLOS) location, in order to evaluate the impact of making a received power sacrifice in exchange for the potential benefits of virtual MIMO. Denoting the un-normalized complex channel coefficient between transmit antenna T and receive antenna R at frequency f and time snapshot i as $g_{R,T,f}^i$, the normalized coefficient $h_{R,T,f}^i$ is:

$$h_{R,T,f}^i = \frac{g_{R,T,f}^i}{\sqrt{\left(\frac{1}{128 \times 16}\right) \sum_{R=1}^4 \sum_{T=1}^4 \sum_{f=1}^{128} |g_{R,T,f}^i|^2}} \quad (1)$$

and the capacity (spectral efficiency in bps/Hz averaged over the bandwidth) is computed at each time snapshot. To produce a single number that facilitates comparison, the mean of the time-varying capacities is then taken. Clearly, the performance of virtual MIMO versus the classical MIMO system will vary over time, but a study of the temporal statistics of the system is deferred to future work.

B. K -Factor

K -factor is the ratio of the power in the deterministic signal path to that in all the scattered components [25]. In a practical measurement, these values can only be estimated from the data available and so a suitable estimator must be chosen. Here, an estimator based on the first and second moments of the envelope of the signal is used, as presented in [25, eq. (7)], where K is estimated by inverting a certain function:

$$\frac{\mathbb{E}\{|x\}|^2}{\mathbb{E}\{|x|^2\}} = \frac{\pi e^{-K}}{4(K+1)} \left[(K+1) I_0\left(\frac{K}{2}\right) + K I_1\left(\frac{K}{2}\right) \right]^2 \quad (2)$$

with $\mathbb{E}\{\cdot\}$ the expectation operator, x the signal, and I_0 and I_1 the zeroth- and first-order modified Bessel functions of the first kind respectively. This function is easily inverted by calculating the moments of the envelope from the data and using a lookup table for K . The nature of this estimator is discussed in [25] and references therein, where it is found to perform similarly to the maximum likelihood estimator for K .

Some care is needed in this calculation particularly when considering the walking measurements. Shadowing will cause the mean level of the signal to fluctuate which, if not accounted for, would appear to decrease the K -factor artificially. Since the measured data spans 1024 snapshots of 128 frequency fingers, the K -factor for an individual channel coefficient is computed for each block of 10 time snapshots by aggregating into a single signal all the 10×128 channel measurements associated with that period. Over this very short time span (61.44 ms), the remaining impact of shadowing should be very small. The K -factor for that channel coefficient is then reported as the mean of these 103 individual calculations. Since the focus of this paper is the comparison between classical and virtual MIMO systems, the mean of the sixteen K -factors produced is reported here. A study of the variations between the individual K -factors would form an interesting item of future work.

C. Spatial Correlation

The correlations amongst the constituent SISO channels in a MIMO system play a crucial role in determining the performance of the system. These correlations can be computed and represented in different ways. In this analysis, where time and frequency domain data is available for all the MIMO links, the correlation co-efficient $\rho_{ij,mn}$ between two channel coefficients h_{ij} and h_{mn} is defined as:

$$\rho_{ij,mn} = \frac{\mathbb{E}_{\tau} \{h_{ij}(\tau) h_{mn}(\tau)^*\}}{\sqrt{\mathbb{E}_{\tau} \{h_{ij}(\tau) h_{ij}(\tau)^*\} \mathbb{E}_{\tau} \{h_{mn}(\tau) h_{mn}(\tau)^*\}}} \quad (3)$$

where \mathbb{E}_{τ} is the expectation of over τ and * denotes complex conjugation. There are 16×16 such correlation coefficients, although $\rho_{ij,mn} \equiv \rho_{mn,ij}$. As with K -factor, shadowing over time — particularly for the walking measurements — will affect the calculation of correlation unless it is handled in some way. For consistency, the same approach as in Section III-B is used, where correlation is computed for blocks of 10 snapshots containing all 128 frequencies and then averaged over the 103 such values for a particular $\rho_{ij,mn}$. The average correlation coefficient of the channel, henceforth denoted simply ρ , is computed by taking the mean of all $\rho_{ij,mn}$ for $(i,j) \neq (m,n)$, i.e., excluding the auto-correlation of each channel coefficient which is unity under the definition in (3).

D. Construction of Virtual MIMO System

As mentioned in Section II-A, there are five locations in Queen Square. Four standing measurements were taken at each location, giving a total of 20 usable datasets in those cases. Two walking measurements were also taken at each location, of which nine gave usable datasets. This results in $\binom{20}{2} = 190$ possible pairs of standing users and $\binom{9}{2} = 36$ walking pairs which act as the virtual MIMO possibilities. Pairs are then assembled into a virtual MIMO system as shown in Fig. 3. It is worth emphasizing the suitability of the arrangement described in the preceding sections for studying a virtual MIMO system: the two users are in proximity to one another, since Queen Square is approximately 150 m^2 ; they are carrying matching devices with the same antennas; and their channels have been normalized so there are no power imbalance problems.

In Section I it was stated that the link of interest is that formed between the virtual MIMO array and the base. There is also the question of the need for the two constituent users to communicate locally. The propagation data available does not include this link, and so it will not be considered in what follows. Important aspects of this link include the additional power, computational load, and bandwidth necessary to operate it successfully, the interference this may cause, and the impact of fading, outage, etc. of this link on the performance of the rest of the system. Some of the papers cited in Section I consider these aspects.

There is also the matter of the feedback load of supporting virtual MIMO, since several users must be coordinated and any closed-loop techniques designed to deal with the differing sources of channel state information (CSI). If such schemes were deployed at the user end, it would also be necessary to

consider the additional computational load and thus battery life reduction that would result. Examples of feedback designs for both complete and partial CSI in virtual MIMO systems, as well as discussions of the load they impose and their impact on system performance, are reported in [11], [26]–[28], with [28] also presenting an information theoretic approach for understanding the different views of the channel the transmitters will have.

IV. RESULTS

This section presents the results that are the key contribution of this paper, beginning with capacity statistics in Section IV-A followed by the propagation parameters of K -factor and spatial correlation in Sections IV-B and IV-C.

A. Capacity

It has been found that three typical capacity outcomes result from using virtual MIMO: the virtual MIMO capacity is (i) better than both; (ii) it is better than only one of; or (iii) it is worse than both the underlying MIMO capacities. Typical examples of these three outcomes are shown in Fig. 4. Here, the 4×4 capacity of each of the two constituent systems is shown compared to the virtual MIMO capacity, at a system SNR of 40 dB (chosen in the high SNR region to focus on the area of the curves where trends have become clear). These are taken from a selection of standing and walking pairs, with the particular locations and orientations shown with each figure.

In Fig. 4, it is clear that the effects of virtual MIMO on capacity are small at low SNRs, but have reached an approximately constant gap by 20 dB. Although the impact of virtual MIMO will obviously vary according to the pairing, SNR gains/losses in the region of 3–5 dB have typically been found, although they do vary down towards 0 dB. The capacity changes seen in Fig. 4 are between ± 5 bps/Hz and ± 1 bps/Hz by the time the curves have reached their linear regions.

To summarize the results over all the pairings considered, Fig. 5 shows the proportions of pairings which result in improvement over both, only one, or neither of the constituent systems, and Fig. 6 shows the individual capacities for all the walking pairs. The equivalent figure for the 190 standing pairs is not included owing to its size and point density, but it shows essentially the same concepts, and the ranges of values in both data sets are given in Table I. Capacities are taken at a high SNR in order to discuss the linear portions of the curves where the trends are clearer. Fig. 5 shows that the capacity is clearly improved in a significant proportion of cases in these measurements, and only rarely is it to the detriment of both constituent systems. However, there is also a substantial proportion of cases in which virtual MIMO is to the benefit of one and the detriment of one constituent. Table I shows, interestingly, that virtual MIMO has clearly lifted the maximum capacity that can be achieved, but for the standing cases has also lowered the minimum. For walking, however, it has both narrowed the range and improved the outer values.

It is worth considering what capacity values of the constituent systems are likely to benefit from the use of virtual MIMO and which would tend not to. In Figs. 7 and 8 the capacity of each individual constituent is shown on the horizontal axes, and the

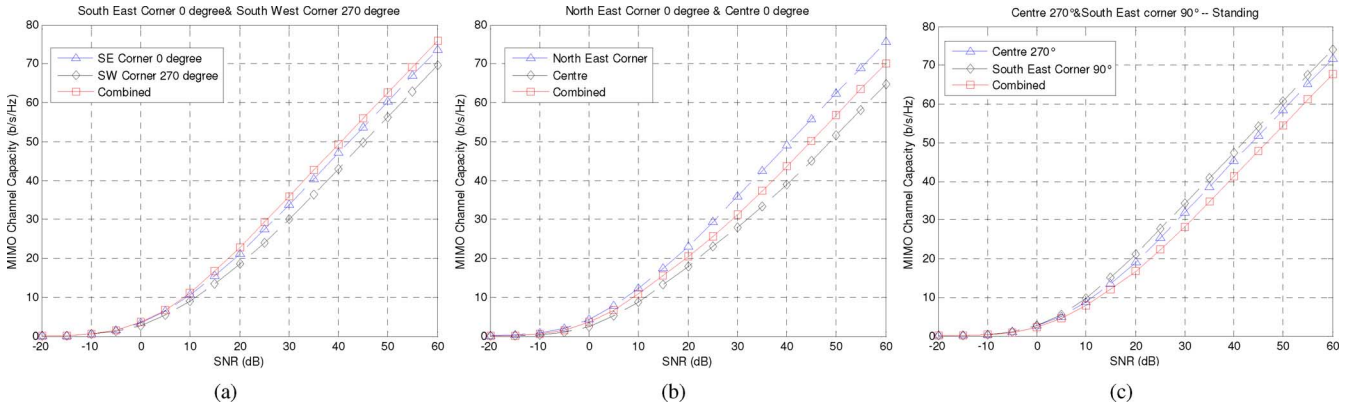


Fig. 4. Examples of the capacity effects of virtual MIMO compared to the constituent classical systems. (a) Virtual MIMO improves over both constituent systems (walking pair). (b) Virtual MIMO improves one and degrades one of the constituent systems (walking pair). (c) Virtual MIMO degrades both constituent systems (standing pair).

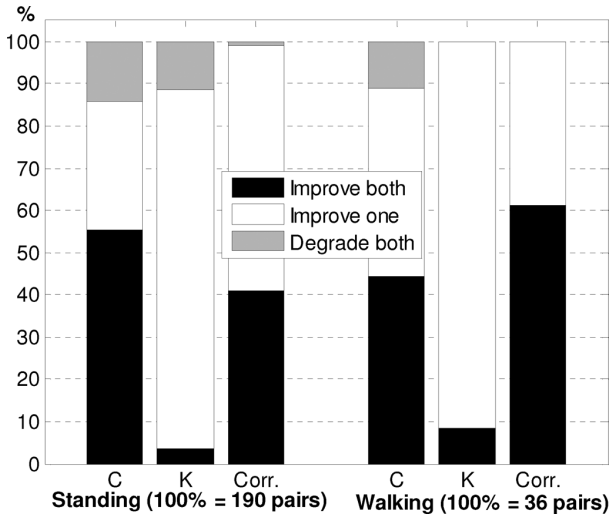


Fig. 5. Proportions of virtual MIMO pairings improving/degrading their two constituent systems.

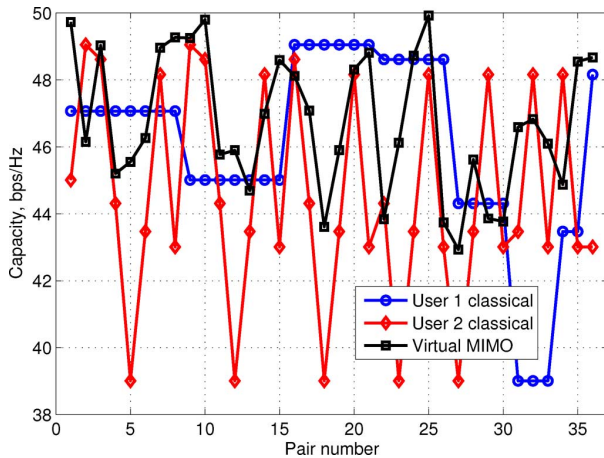


Fig. 6. Classical and virtual MIMO capacities for all walking pairs.

number of possible virtual MIMO pairings that improve its capacity is shown vertically. Although the individual capacities fall in a narrow range around 46 bps/Hz, there is a clear trend

TABLE I
RANGE OF CAPACITY, K -FACTOR AND SPATIAL CORRELATION VALUES

Parameter	Standing range		Walking range	
	Classical MIMO	Virtual MIMO	Classical MIMO	Virtual MIMO
Capacity, bps/Hz	42.4 – 50.0	37.7 – 52.5	39.0 – 49.1	42.9 – 49.9
K -factor, dB	-2.8 – +6.3	-2.3 – +6.4	-2.7 – +7.0	-2.5 – +6.1
Correlation	0.23 – 0.68	0.24 – 0.62	0.28 – 0.74	0.24 – 0.59

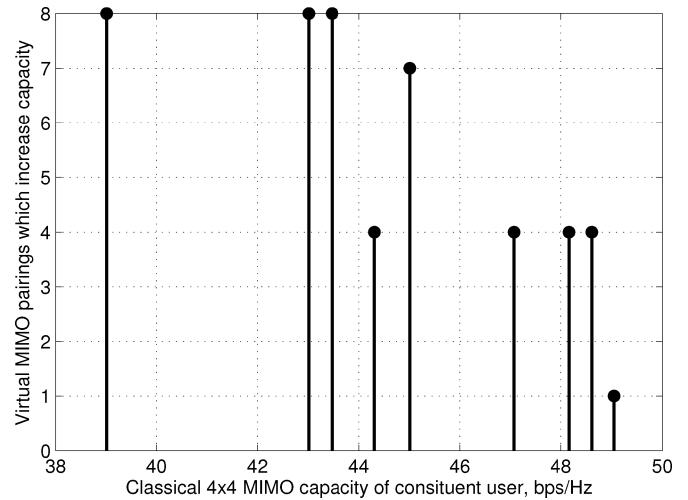


Fig. 7. Classical capacities vs. how many of the 8 possible virtual pairings would increase capacity, for walking pairs.

that above about 46.5 bps/Hz, in at least half of cases the capacity is not improved by virtual MIMO but with only a small fall in capacity to about 44 bps/Hz, the significant majority of cases give a capacity improvement. This suggests that the impact of virtual MIMO is quite sensitive to the nature of the constituent classical users.

These results indicate clearly that virtual MIMO is not always desirable. Capacity in a MIMO system is a dependent quantity, and varies in response to the many parameters that affect the quality of the propagation channel. The analysis that

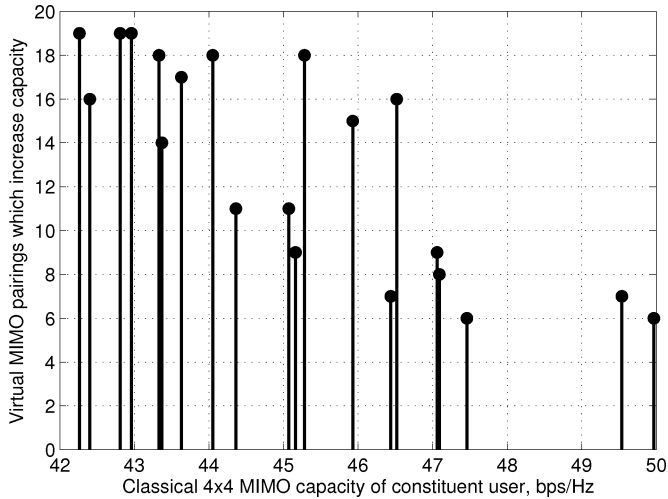


Fig. 8. Classical capacities vs. how many of the 19 possible virtual pairings would increase capacity, for standing pairs.

follows will try to account for the changes in capacity by considering what impact virtual MIMO is having on the propagation parameters compared to the two constituent channels. Since two key parameters affecting the capacity of MIMO systems are K -factor [29], [30] and spatial correlation [4], [31], these two will now be investigated in a similar way to capacity.

B. K -Factor

The various K -factors that are found at the individual walking locations and the virtual MIMO pairings are shown in Fig. 9 (with the equivalent, much larger, figure for standing omitted). Most of the classical K -factors are between approximately ± 3 dB, with one unusually line-of-sight (LOS) location at $+7$ dB. This shows that the virtual system’s K -factor often falls between the two constituent systems’, with some significant increases in K at those locations where one constituent user has a K -factor much greater than the other. The tradeoff for this is that the K -factor of the more-strongly LOS location is reduced in such cases. This is because taking only eight of the sixteen SISO links from each user, and reporting the mean of the combined set, acts naturally to average out the differences between the overall mean K -factors of the two constituent users. Thus, even where two NLOS users, with mean $K < 0$ dB are combined, the virtual system will tend to have a K -factor larger than one and smaller than the other. In the very small number of cases where the virtual system’s K -factor lies outside the two constituent values, this is the result of the particular links chosen from each user having individual K -factors somewhat above or below the overall mean value reported for that location.

In both walking and standing pairs, Table I indicates that virtual MIMO has narrowed the range of K -factors, tending to make the system more predictable, but has tended to increase the lower levels of K , as already noted. It has made little difference to the highest K values while standing but provided a reduction of nearly 1 dB for the worst walking values.

The stem graphs in Figs. 10 and 11 show in a similar way to those for capacity, the number of virtual MIMO pairings that

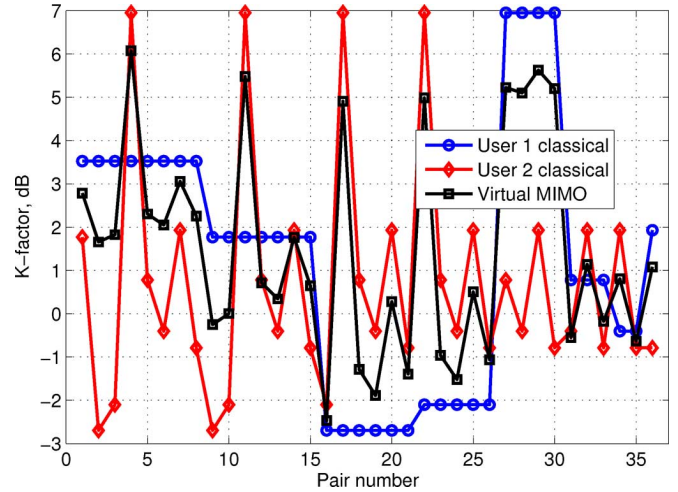


Fig. 9. Classical and virtual MIMO K -factors for all walking pairs.

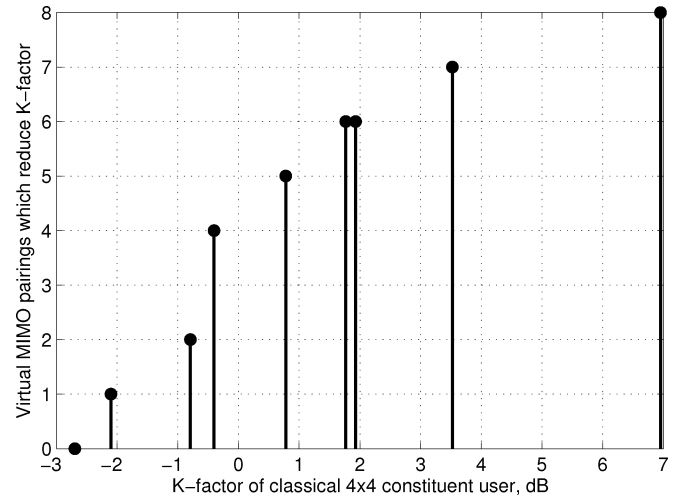


Fig. 10. K -factors of classical constituent users vs. how many of the 8 possible pairs of virtual channels would reduce K , for walking pairs.

reduce the K -factor compared to an individual classical user. There is a much stronger trend shown here than with capacity, demonstrating that K -factor reduction is increasingly likely for virtual MIMO as K becomes larger (though this is usually beneficial for MIMO, it can make the demodulation problem harder as the channel fluctuates more widely). For the walking pairs, the threshold for 50% of pairings to reduce K -factor is -0.5 dB and for standing pairs it is $+2$ dB. As a result, some 60% of locations (5 out of 8 walking; 11 out of 19 standing) have an improved K -factor for at least 50% of all possible pairings, and virtually all locations have at least one possibility to improve it. Referring to Fig. 5, however, there are very few locations where both the constituent K -factors are improved upon — just 4% for standing and 8% for walking pairs. The proportion of locations with virtual MIMO capacities above those of both constituents is much higher, so it is difficult to ascribe that improvement to K -factor effects alone, and spatial correlation may also play a role, as studied next. Insofar as antenna patterns influence such parameters, they will also be of relevance.

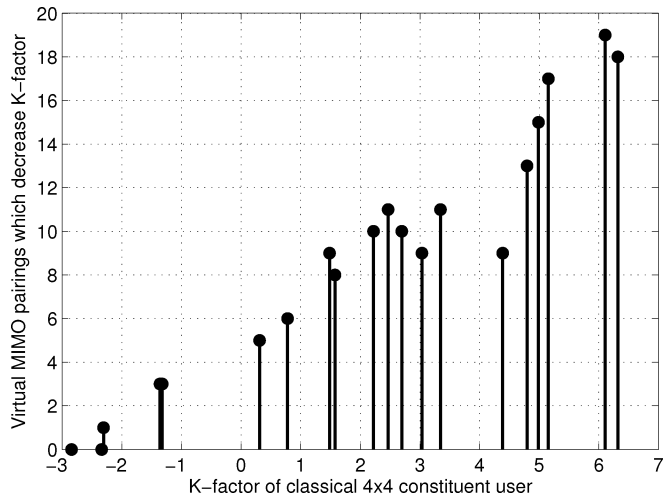


Fig. 11. K -factors of classical constituent users vs. how many of the 19 possible pairs of virtual channels would reduce K , for standing pairs.

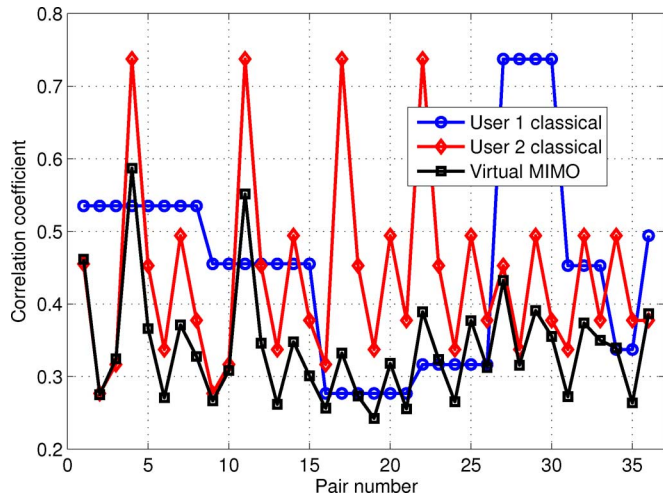


Fig. 12. Classical and virtual MIMO correlations for all walking pairs.

C. Spatial Correlation

The overview of all walking correlation values shown in Fig. 12 makes it apparent that the application of virtual MIMO tends to decrease correlation in many cases. Even for values of ρ already well below 0.5, reductions to below 0.3 are still possible and, unlike in the case of K -factor, the virtual system's correlation is often lower than in both the constituent systems. The main exceptions to this are when one correlation value is much higher than the other; of particular note is the location with $\rho = 0.73$. Even there though, the reduction from that value can be substantial: at "pair 17" the virtual system's correlation is far lower at 0.34. This is a key benefit of virtual MIMO: the extremely wide separation of the two users involved would clearly reduce correlation among the four antennas substantially in most real-world cases with reasonable amounts of scatter away from the MS and BS [4]. The ranges reported in Table I echo these observations for both standing and walking pairs, with clear reductions in the higher correlation values particularly.

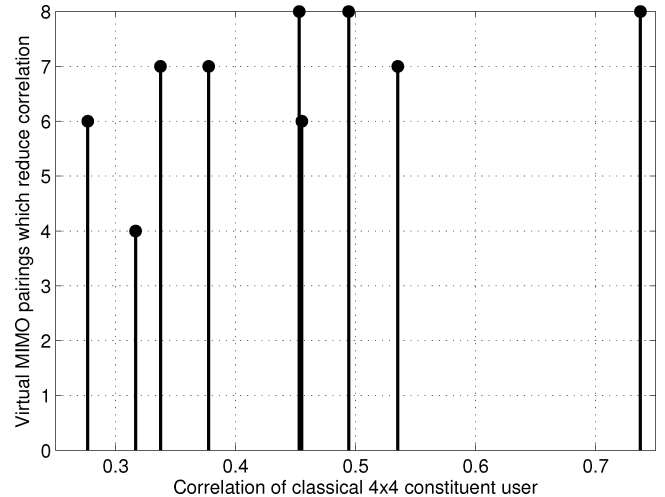


Fig. 13. Correlations of classical constituent users vs. how many of the 8 possible pairs of virtual channels would reduce correlation, for walking pairs.

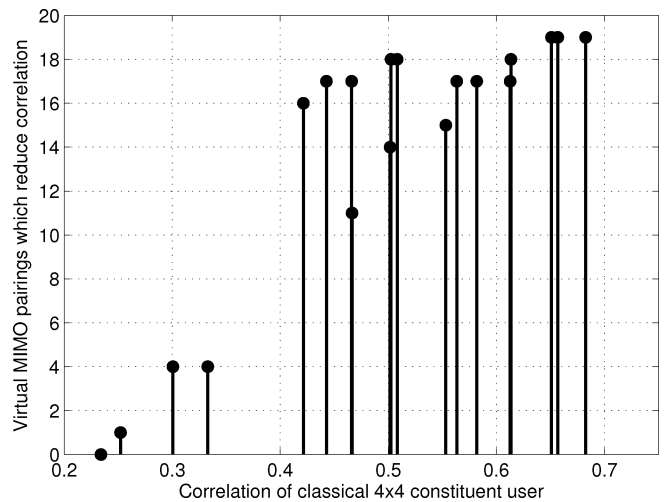


Fig. 14. Correlations of classical constituent users vs. how many of the 19 possible pairs of virtual channels would reduce correlation, for standing pairs.

Considering the stem graphs in Figs. 13 and 14, it is seen that to be able to reduce correlation with 50% of possible pairings, any correlation found whilst walking will suffice, and any $\rho \geq 0.42$ for the standing cases. In fact, the same thresholds apply for correlation reduction in 75% of possible pairings, with only a few exceptions. The walking results are particularly strong when viewed like this, since the quickly changing nature of the environment at the two routes being followed means that any residual correlation remaining after the very wide spacing is considered falls away quickly, as does any short-term correlation that arises during the walks.

The proportions of cases in Fig. 5 that give a correlation reduction over both constituent systems are considerably larger than those for K -factor, and are closer to the proportions for when capacity improves over both. Reducing spatial correlation in a MIMO system has long been known to increase capacity [4], [31]. It seems likely therefore that correlation reduction is having a larger effect on capacity increase than is K -factor reduction. Of course, it is important to bear in mind that there are other propagation parameters than K and ρ (not to mention

the different correlations in the system) that also affect capacity and they too will be playing some role. This is particularly true of the walking results in Fig. 5 when capacity is reduced compared to both constituent systems, since the reduction cannot otherwise be accounted for as neither K nor ρ are ever poorer than both. A study of the other pertinent propagation parameters could also aid the analysis of the mixed performance cases from Fig. 5 where attributing the proportions to either K or ρ individually (or even jointly) is otherwise difficult. In this respect, parameters with a significant impact on spatial correlation will be of greatest importance, notably the distributions of angular spread and angles of arrival and departure.

V. SUMMARY AND CONCLUSIONS

This paper has presented results using measured data to consider to what extent virtual MIMO is able to provide improved capacity and radio propagation parameters over classical MIMO in the locations studied. It was found that virtual MIMO does not always provide a capacity or propagation advantage and therefore that establishing some metrics by which “good” cases can be identified is worthwhile. In this respect, the proportions of cases where virtual MIMO provides a benefit were evaluated.

The capacity of the virtual 4×4 MIMO system was higher than both of the two constituent systems’ in about 50% of pairings for both standing and walking users, but in a few exceptional cases could be worse than them both. The lower the capacity of the constituent systems, the more likely it was to be improved by virtual MIMO. The K -factor of the virtual MIMO system was found most often to fall between those of the two constituent systems and was rarely improved over both constituent K -factors. Correlation in the virtual MIMO system was reduced compared to the constituent systems much more frequently than K -factor. It was exceptionally rare for correlation to be increased by virtual MIMO as would be expected given the very wide separation of the two constituent users. These overall statistics were related to the parameters of the constituent classical systems in order to produce thresholds on capacity, correlation, and K -factor to indicate when a particular user would benefit in at least 50% of the possible virtual pairings. The metrics, statistics, and methodology presented here may be useful in evaluating whether virtual MIMO would be suitable in other environments, both measured and modeled.

This variability of the benefit of virtual MIMO found in this work is clearly the result of the interplay of propagation parameters and therefore future work should study a wider gamut of such parameters that are known to affect MIMO capacity, most notably angular spread and angle-of-arrival and departure distributions and couplings. It would also be worthwhile to study the temporal nature of the results found here, to see how often within these high level statistics it might be desirable to switch between virtual MIMO and classical MIMO and how temporally localized the virtual system’s benefits are. Other important aspects for future consideration include analysis of the other possible antenna subsets that could be chosen from the constituent users to see how the comparative statistics may be improved with a judicious choice, and the incorporation of the cooperative link into a full system comparison.

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