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Keeping Mobile Communication Channels Static With Antenna Counter-Movements

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ABSTRACT This work investigates how well mobile wireless communication channels can be kept static during device movements when the antenna performs appropriate counter-movements. A prototype is built and proof-of-concept experiments are performed for linear movement in the 2.45 GHz industrial, scientific and medical (ISM) frequency band in an anechoic chamber and in a static office environment. The technique is assessed quantitatively. The measured data show that fluctuations of receive power can be decreased by a factor of thousand as the antenna no longer experiences small scale fading. Changes in the phase are brought down to values smaller than 10° and no longer scale with the traveled distance. Mathematical channel models are derived from the measurements.

INDEX TERMS Antennas, communication channels, mobile communications, static, time-varying systems, vehicular.

I. INTRODUCTION

Vehicular and mobile wireless communication channels are currently widely handled by channel coding and signal processing techniques. Changes in wireless channels are addressed by rapidly updating the channel state information, usually based on pilot symbol aided channel estimation techniques [1], [2]. However, pilot based channel estimation increases overhead as systems use an increasing number of antennas. New transmission schemes, that aim to utilize the channels of multiple antenna system, show significantly reduced performance when operating under outdated channel state information [3].

Several techniques are in use that aim to keep channels static on a physical basis by compensating deterministic effects. Deterministic influences on wireless communications channels are well known. The simplest sources of deterministic changes are arguably device movements and rotations as they change the free space path loss between transmitter and receiver, change the angle in the antenna radiation pattern and move the antenna through small scale fading interference patterns. Mechanical stabilizers are employed to keep the position and angle of the antenna to address vibrations and tilting in directional radio links an radar applications [4], [5]. Rockets and projectiles that rotate during flight to increase stability, can compensate such rotations with cylindrical arrays and beamforming [6]. Satellite antennas were already despun for Intelsat III in the 1960s [7]. A technique for the correction of beam aberration for space antennas is presented in [8]. A series of antennas on a car was used in [9] to keep the channel static between the moments of channel estimation and transmissions, but this required either interpolation or that the transmissions occurred only at the exact times when a subsequent antenna was in the spot of the predictor antenna [10].

Automation and control techniques have advanced tremendously in the past decades and can now stabilize complex systems such as triple inverse pendulums [11]. Active suspension systems can counter-act movements of vehicles on uneven roads since the 1980s [12]. In robotics counter-movements are now routinely performed in response to random forces [13], [14]. Medical devices detect and counter-act movements, such as robotic canes for senior citizens [15] and robotic spoons for tremor patients [16].

However, to the best of the authors knowledge, such physical techniques are not used to keep vehicular and mobile communication channels static and no works exist that investigate such methods for these applications. Consequently,

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no performance estimates are known and no channel models are available. This article aims to close this gap with proof-of-concept experiments on the most basic principle, that is that the antenna keeps the channel static by performing appropriate counter-movements simultaneously to device movements.

Compared to previous work on stabilizers [4], [5], the counter-movements are several wavelengths long. They can be combined with techniques that address beam misalignment [6]–[8]. Counter-movements keep the channel static at all times and not just between discreet positions [9], [10].

Contribution — It is demonstrated experimentally that mobile wireless communication channels can be kept static under linear device movement by performing counter-movements of the antenna over a wide distance of several wavelengths. The performance of the technique is assessed quantitatively based on measurements in an anechoic chamber and in an office environment in the 2.45 GHz industrial, scientific and medical (ISM) frequency band. It is considered that the counter-movements are limited by the device size, e.g. for smart phones, for which it is found that channel can be kept *piecewise* static. Channel models are proposed based on the measured data.

Nomenclature — Antennas, that keep the channels static by performing counter-movements are referred to as *channel static antennas* to distinguish them from regular antennas that are fixed to their devices and move with them.

II. THEORETICAL CONSIDERATIONS

Movements of devices generally change the mobile wireless communication channels that these devices experience, if the antennas are fixed to the device (which is the state of the art today). This is sketched in Fig. 1a, where an antenna is mounted inside a moving volume. The volume's movement changes the antenna's position and consequently changes the amplitude, phase and frequency of a channel to a second antenna. The antenna could prevent this by simultaneously performing a counter-movement to stay in its position relative to the second antenna (Fig. 1b).

However, this concept is difficult to implement in practice, where antennas are mounted on devices. The antenna is then unable to freely move through the volume. For practical applications, it is therefore reasonable to instead consider antennas that are mounted on a perfect conductive sheet of infinite size (e.g. in x-y plane, see Fig. 2) that moves in its plane. The antennas can perform counter-movements on the surface. The space underneath the sheet is now entirely irrelevant to the channel, because electromagnetic waves do not penetrate it. From a design viewpoint, the space below the sheet can house arbitrary components.

Antennas that are mounted on large ground planes are in widespread commercial use as most electric and electronic devices are surrounded by conductive sheets such as casings, hulls, and chassis for reasons of electromagnetic compatibility (EMC), mechanical stability and protection. As a welcome coincidence, drag considerations result in airplanes, cars, trains, ships and rockets that are designed to be long in the direction of their movement and large distances for counter-movements are available. Movements of these devices perpendicular to their hulls are typically small during normal operation.

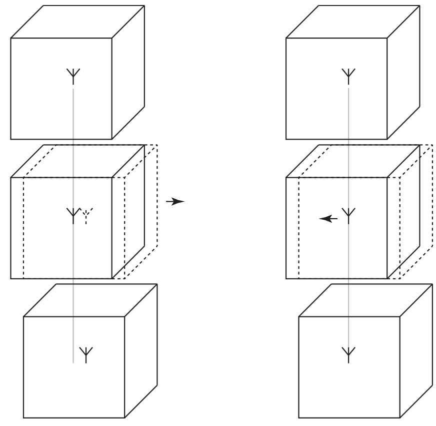


FIGURE 1. In theory it is quite trivial that antennas, that are being moved, could compensate channel changes by performing a counter-movement. a) *Top:* An antenna is mounted in a volume. *Center:* The volume moves. *Bottom:* This movement would generally change the channel to a second antenna (not depicted) at an arbitrary position. b) *Top:* An antenna is mounted in a volume. *Center:* The volume moves, but the antenna performs a counter-movement. *Bottom:* The channel stays static because nothing has changed; except that an imagined volume was moved.

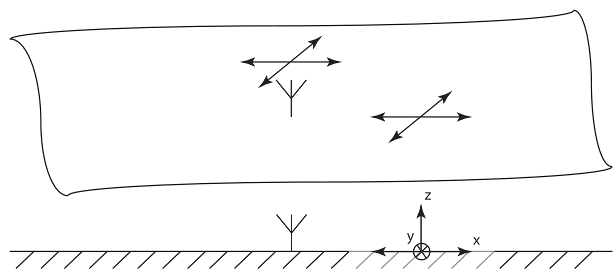


FIGURE 2. An antenna on a perfect conductive sheet of infinite size can keep its channel static under sheet movement in x-y plane by performing a counter-movement on the surface.

Objects can be added around the volume, or above the ground plane, which can reflect electromagnetic waves, scatter them, absorb, refract, amplify and so on, as is sketched in Fig. 3. The channel itself becomes more complex in this environment, but the antenna's ability to keep the channel static is not impeded. The antenna can keep the channel static with counter-movements as long as the other objects don't move or change their relevant material properties.

In practice, the counter-movements of the antenna are of course limited by the size of its device. This is considered in Sec. III-C. To avoid falling off, the antenna backs off and chooses a new position on the device. There, the antenna again performs counter-movements to stay in its position until it reaches a device edge and so on. Therefore, the antenna can keep the channel *piecewise* static for long movements of mobile devices (see Fig. 4).

In communication systems that connect several moving stations, such as vehicular ad hoc networks (VANet), each node can individually keep its antenna static. It should

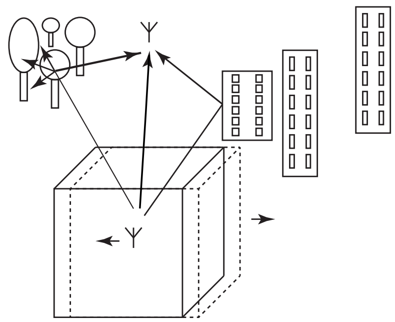


FIGURE 3. Even with the addition of complex objects a counter-movement can keep the channel static, as long as the objects don't move or change relevant properties.

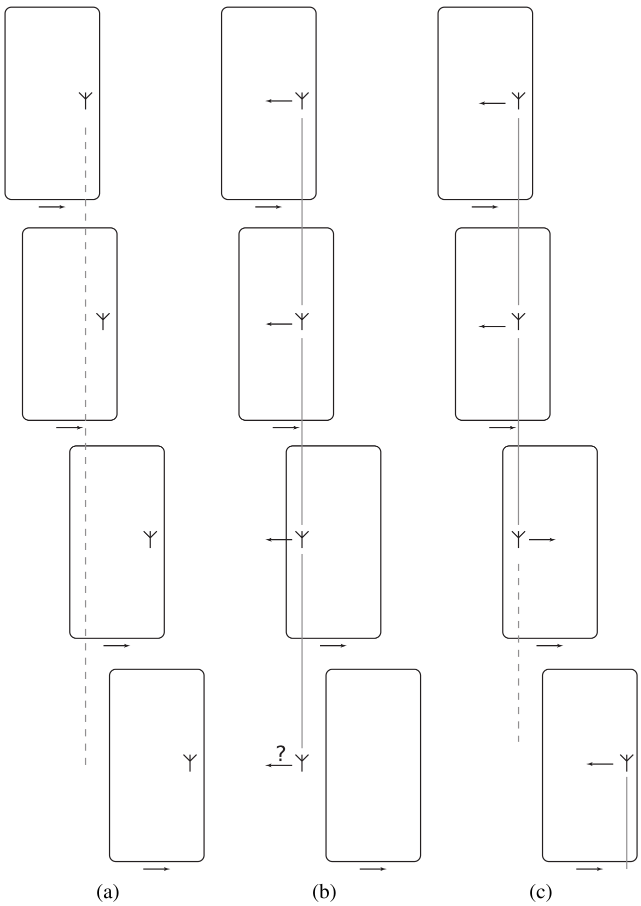


FIGURE 4. a) On a state of the art mobile device the antenna is fixed to the device and moves with it, which changes the wireless channel. b) The antenna performs a counter-movement to stay in its original position, but the antenna can not move beyond the size limitations of the device (bottom). c) The antenna again performs a counter-movement, but it obeys the size limitations of its device. When it reaches the end, it moves to a different position on the device. The channel static antenna for the mobile device therefore keeps the channel *piecewise* static.

be noted that an antenna's position on a device influences its radiation characteristics [17], [18] and that such device specific influences are avoided within the scope of this work.

Estimates on how long channels can be kept static with the investigated method are calculated exemplarily for antennas mounted on cars and phones. Assuming the length of typical cars as 4 m [19] and considering a speed limit of 150 km/h or 93 mph, it would be then possible to keep channels static for 96 ms. Assuming 6 cm for antenna movement on smart phones [20] at a speed of 5 km/h [21], it would be possible to keep channels static for 43.2 ms. These times are long e.g. when compared to the 10 ms radio frame and 1 ms subframe durations of LTE and 5G New Radio [22].

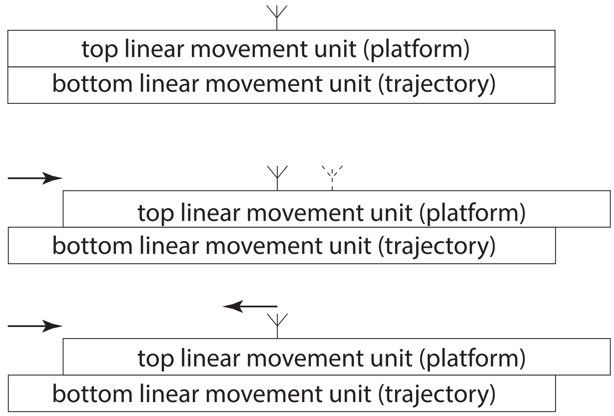


FIGURE 5. In the experiment an antenna is mounted on two linear movement units (top). The bottom unit moves the antenna (middle) and the top unit performs counter-movements (bottom).

III. EXPERIMENTAL EVALUATION OF CHANNEL STATIC ANTENNAS UNDER FINITE, LINEAR PLATFORM MOVEMENT

The experiments are performed on the Vienna MIMO Testbed [23]–[25]. The above considerations are limited for the experimental evaluation. Without loss of generality, the trajectory is limited to a straight line. The antenna is mounted on two high-precision linear movement units for computerized numerical control (CNC) machines. The bottom unit moves the platform and the top unit moves the antenna to counter the platform's movement. This configuration is sketched in Fig. 5. Narrowband channel measurements are performed in the ISM frequency band at 2.45 GHz. The perfect conductive ground plane of infinite size is approximated by an aluminum disc with a diameter of 180 mm ($\approx$ 1.5 λ). The antenna is built as a quarter-wavelength monopole antenna. It is elevated by a 26 cm tall column such that a coaxial cable can be connected to a subminiature version-A (SMA) connector on the bottom. An identical second quarter-wavelength monopole antenna is placed in the same room at a distance of approximately 2 m. Both antennas are connected to a vector network analyzer (VNA) with coaxial cables. Before the experiments, the coaxial cables were calibrated at the antenna ports with a through, open, short, match (TOSM) kit. The measurements are automated with a laptop computer that controls the platform movement, the antenna movement and the VNA. The platform is moved in steps, because the VNA measurements take some time. In one step, the platform is moved 0.02 λ, then the setup waits for 0.2 s to wear off vibrations from acceleration/deceleration, then the VNA measurement is performed. Therefore, Doppler shift [26] can not be measured directly. However, it is obvious that the frequency would not change significantly, as the the instantaneous angular frequency is the time derivative of the phase and the measured phase remains practically steady with the channel static antenna.

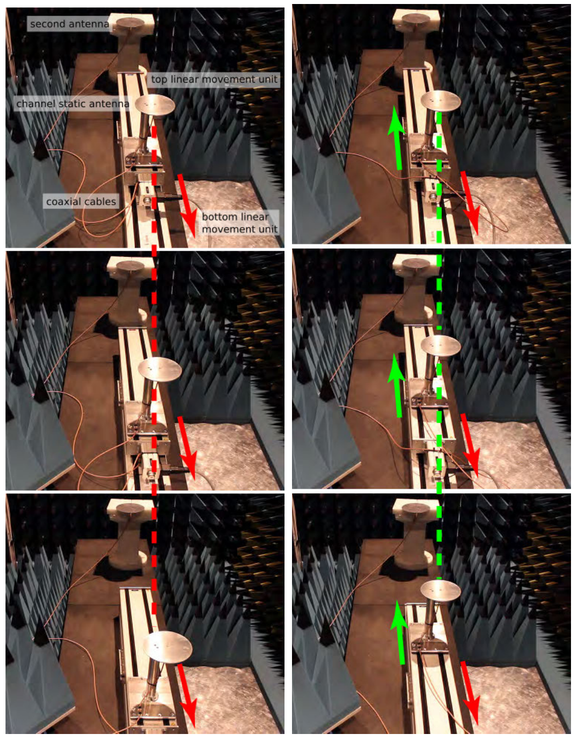
Three measurements were performed in each setup. First, the platform was moved over a distance of $6\,\lambda$ ($\approx$ 73 cm). The antenna was fixed to the platform and moved with it. Second, the platform was moved over $6\,\lambda$ and the antenna countered the platform's movement by simultaneously performing a counter-movement in the opposite direction. Third, both the antenna and the platform remained still in their initial positions. The third measurement acts as a reference to quantify the channel changes that are caused by the environment, which are not compensated by the investigated method. It is an achievable upper performance bound in the office environment.

A. MEASUREMENTS IN AN ANECHOIC CHAMBER

The first investigation was performed in an anechoic chamber. An anechoic chamber is a simple environment in terms of wireless channels. Multi-path propagation is heavily attenuated and amplitude variations from antenna movements are expected to be small. The linear movement units are placed on an absorbing walkway in the chamber. The second antenna is placed on a column made from hard foam with air-like electromagnetic properties (Rohacell HF, [27]). The antennas are connected to the VNA, which is placed outside the chamber, via a feed through. The unit that controls the linear movement units had to be placed inside the chamber due to a lack of suitable feed-throughs, but it was covered by pyramid absorbers. Fig. 6 shows photographs of the experiment.

B. MEASUREMENTS IN AN OFFICE ENVIRONMENT

The experiment is repeated in an office environment (see Fig. 7). This is a typical environment for WLAN that operates in the 2.4 GHz frequency band [28], it will be a typical setting for 5G [29] and especially machine type communications [30]. From an electromagnetic viewpoint, this is a complex environment that contains a large number of different materials which are arranged in complex shapes. The resulting small scale fading is typically described with statistical methods [31], [32]. Although, channels in such environments are complicated, they are static and not intrinsically time-variant, because the objects don't move and don't change their material properties [33]. The measurement scripts were started with a timer such that no people were present in the room, to avoid influences of moving researchers. Fig. 8 shows the setup at selected times during the measurement.



(a) (b)

FIGURE 6. A platform moves towards the front in an anechoic chamber. a) The antenna is fixed on the platform and moves with it. b) The antenna counters the platform's movement with a counter-movement.

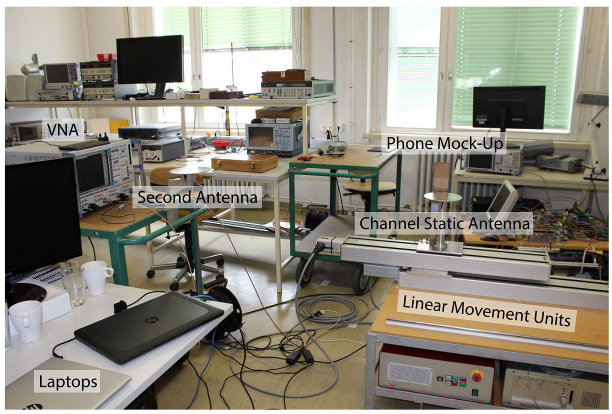
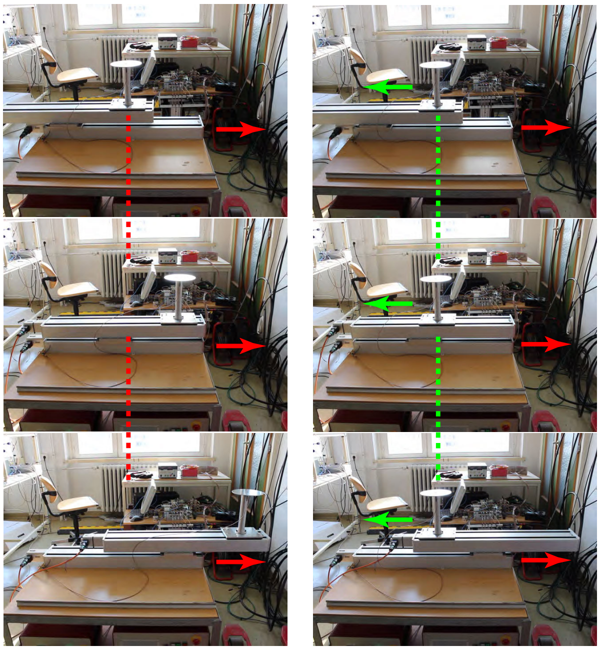


FIGURE 7. Photograph of the measurement setup and the surrounding office environment. The room contains objects with complex shapes from a variety of materials.

C. MEASUREMENTS WITH COUNTER-MOVEMENTS CONSIDERING A LIMITED DEVICE SIZE

The performance of channel static antennas for small mobile devices is investigated by limiting the distance over which the antenna can perform counter-movements to $0.5\,\lambda$ (about 6 cm). This is a feasible distance considering the width of current smart phones [20]. A thin cardboard smart phone mockup is added behind the antenna as a visual reference. Its influence is expected to be negligible. The device mockup is moved over a distance of $6\,\lambda$ that far exceeds its width.



(a) (b)

FIGURE 8. A platform moves from left to right in an office environment. a) The antenna is fixed on the platform and moves with it. b) The antenna counters the platform movement to stay in its position relative to its surroundings.

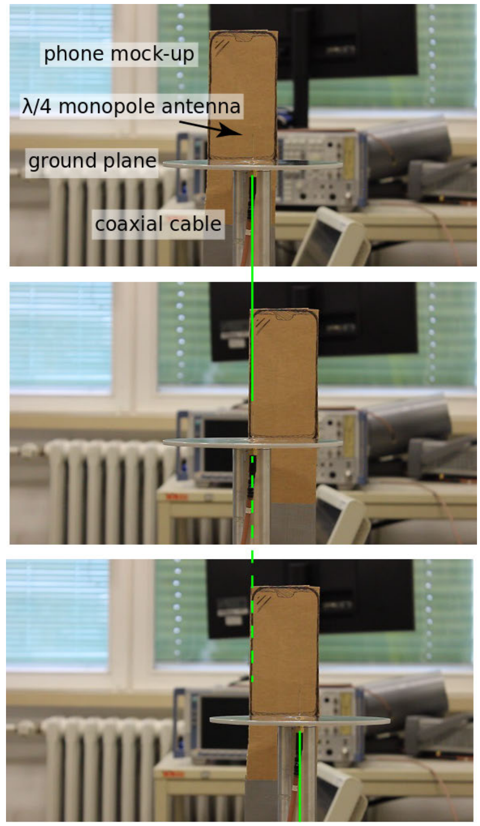


FIGURE 9. The antenna keeps the channel static within the size limits of a mobile device. Top to bottom: The antenna performs counter-movements to stay in its position relative to outside observers. The antenna can not move beyond the device. It moves to a new position at which it keeps the channel static.

Photographs that illustrate the working principle are shown in Fig. 9.

IV. MEASUREMENT RESULTS AND QUANTITATIVE EVALUATION

The measured scattering-parameters (S-parameters) of the channels are shown in Fig. 10. The regular moving antenna and the channel static antenna are plotted as a function of the length in wavelengths that they moved away from their initial positions. Measurements without movement are shown as a reference. These measurements are plotted over time for a similar duration as the two other measurements. The phase of the regular antenna is wrapped over 2π in the plot such that the results without movement and with the channel static antenna are still visible.

In the anechoic environment, the amplitude variations are quite small (Fig. 10a), as was expected. With the channel static antenna, there are small residual changes in the absolute values of the scattering parameters of 2.5 dB (peak-to-peak). The overall variation and the ripple are smaller with the channel static antenna than with the regular moving antenna (4.2 dB peak-to-peak), but there is significantly more variation in amplitude than in the reference measurement without movement (0.8 dB peak-to-peak). Fig. 10d shows the phase difference between the two antennas. As expected in an anechoic environment, the channel changes are primarily revealed in the phase difference between the two antennas. The phase difference to the regular antenna steadily increases, as it moves away from the second antenna. Measured values are close to the theoretical phase shift of 2π per λ distance. The channel static antenna keeps the phase almost perfectly static (0.29 rad peak-to-peak, $\sigma^2 = 0.0066\,\text{rad}^2$) over a long distance of platform movement (6 λ).

The channels from the office environment are plotted in Fig. 10b and Fig. 10e. As expected, the results confirm that the wireless channel is not time-variant on its own; it stays practically the same without antenna movement. When the antenna is fixed to the platform and moves with it, the measured channel is characterized by the deep fading notches that are typically observed in office environments [31]. The changing channel is a direct result of the antenna's movement through the multipath-propagation environment with constructive and destructive interference — the antenna experiences the small scale fading environment as fast fading. When the platform movement is compensated by the antenna, it no longer moves through the multipath interference pattern and the channel is approximately static. Without movement, the channel changes only by 0.16 dB, while it changes by 31.69 dB with the regular antenna (peak-to-peak). The channel static antenna compensates the variations by a factor of 1000. Residual changes in received power are less than a factor of 2 (measured as $\leq$ 2.35 dB). The phase is

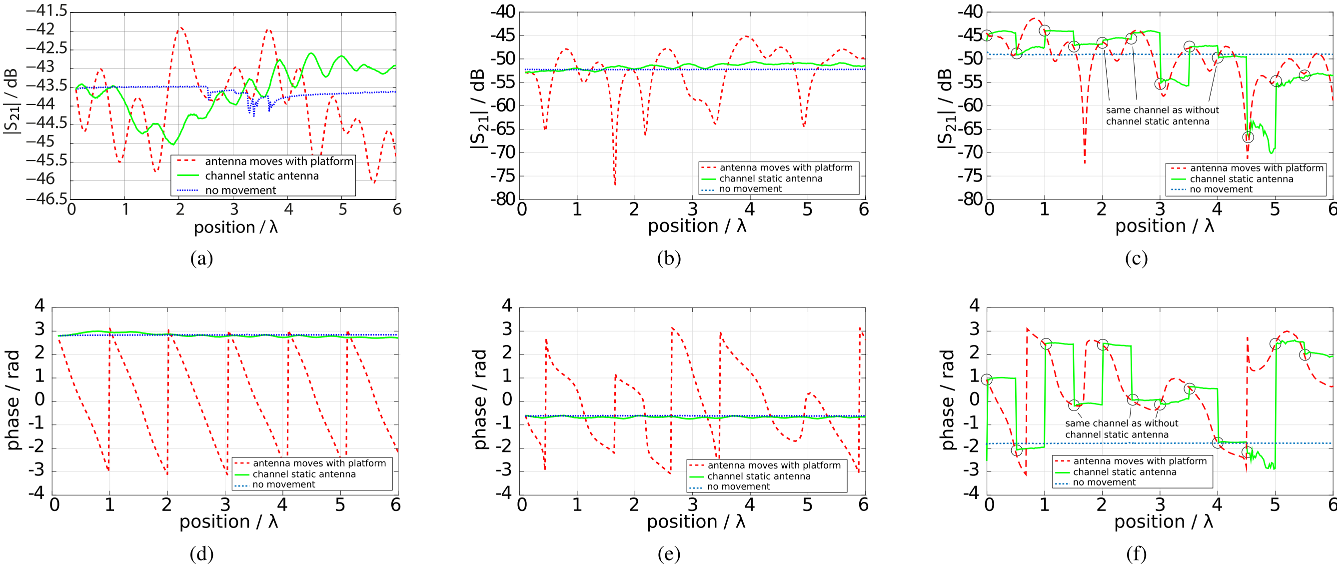


FIGURE 10. Measured S-parameters with the channel static antenna. *left column (a,d):* in the anechoic chamber, *center column (b,e):* in the office, *right column (c,f):* in the office considering a limited device size for counter-movements of 0.5 λ. *top row (a,b,c)* amplitude and *bottom row (d,e,f)* phase. The measurements without movement are shown as reference. There, the antenna stands in the initial position for a time period similar to the other two measurements. The phase is wrapped around 2π for convenient viewing.

TABLE 1. Measured mean μ, maximum (peak-to-peak) and variances σ^2 of channel changes.

		amplitude			phase		
		μ / dB	max / dB	σ^2 / dB^2	μ / rad	max / rad	σ^2 / rad^2
anechoic	regular (wrapped 2π)	-43.0	4.15	1.0338	0.043	6.265	3.21
	regular (not wrapped)	-”-	-”-	-”-	-15.66	36.341	109.99
	channel static antenna	-43.6	2.45	0.4236	2.83	0.293	0.0066
	no movement	-43.6	0.80	0.0190	2.85	0.056	$6.11 \cdot 10^{-5}$
office	regular (wrapped 2π)	-52.9	31.69	28.5	-0.21	6.265	2.81
	regular (not wrapped)	-”-	-”-	-”-	-12.52	21.904	41.81
	channel static antenna	-51.6	2.35	0.3595	-0.680	0.146	$9.89 \cdot 10^{-4}$
	no movement	-52.2	0.16	0.0010	-0.620	0.027	$2.68 \cdot 10^{-5}$
office (device size limited)	regular (wrapped 2π)	-49.9	30.95	23.7	0.601	6.223	2.50
	regular (not wrapped)	-”-	-”-	-”-	-6.517	12.847	10.11
	channel static antenna		See Tab. 2			See Tab. 2	
	no movement	-49.0	0.64	0.0032	-1.796	0.115	$5.53 \cdot 10^{-5}$

kept almost completely static by the channel static antenna. In the measured scenario, the phase stays within 0.15 rad (8.39°) peak-to-peak and $9.9 \cdot 10^{-4}$ rad^2 variance over a platform movement of 6 λ.

The measured channels with limited counter-movements in the office are given in Fig. 10c and Fig. 10f. The results show that wireless communication channels can be kept piecewise static under device movement by performing a counter-movement of the antenna within the size limitations of the device. Again, a regular antenna experiences large variations in the channel and deep fading notches with 20 dB reduced receive power as it moves through the small-scale fading environment and consequently lowers the signal-to-noise-ratio (SNR). However, the channel static antenna no longer experiences small scale fading as fast fading when moving through the environment. By performing counter-movements, the antenna keeps the channel practically static until the antenna reaches the end of the device and has to move to a new channel. The initial static channel coincides with the channel that the regular antenna experiences at this position. It must be noted, that the antenna keeps the wireless channel static, but that it does not ensure, that it keeps a good channel, e.g. the channel at distance 4.5 λ coincides with a fading notch and this position is kept although the channel would get better.

The channel variations are listed in Tab. 1. For the measurement that considers the device size, the values for all static intervals are given in Tab. 2. The residual channel changes with the channel static antenna are attributed to the metallic linear movement unit that protrudes underneath the antenna, as it distorts the wave propagation and therefore influences the channel. The residual changes are too large to be caused by the repeat accuracy of the linear positioning unit of 0.02 mm (0.00016 λ). Back-to-back measured changes from bending and moving cables are also lower ($\sigma^2_{amp} = 5.6 \cdot 10^{-5}$/dB^2 and $\sigma^2_{phase} = 6.5 \cdot 10^{-5}$ / rad^2).

TABLE 2. Measured mean, peak-to-peak values and variances of channel changes with the channel static antenna that considers device size limitations in the office environment.

	amplitude			phase		
interval	μ / dB	max / dB	σ^2 / dB^2	μ / rad	max / rad	σ^2 / rad^2
0 - 0.5 λ	-44.3	0.88	0.054	0.993	0.094	0.00058
0.5 - 1 λ	-48.0	1.75	0.376	-2.005	0.120	0.00101
1 - 1.5 λ	-44.0	0.17	0.003	2.471	0.065	0.00052
1.5 - 2 λ	-46.9	0.34	0.008	-0.111	0.120	0.00107
2 - 2.5 λ	-45.7	0.52	0.003	2.411	0.109	0.00138
2.5 - 3 λ	-44.3	0.46	0.023	0.060	0.044	0.00014
3 - 3.5 λ	-54.9	1.59	0.270	-0.019	0.234	0.00616
3.5 - 4 λ	-47.3	0.35	0.008	0.577	0.096	0.00104
4 - 4.5 λ	-49.5	0.39	0.009	-1.738	0.031	0.00010
4.5 - 5 λ	-66.2	6.80	5.018	-2.493	0.779	0.06733
5 - 5.5 λ	-54.8	2.05	0.506	2.537	0.162	0.00181
5.5 - 6 λ	-53.4	0.73	0.035	2.015	0.213	0.00385

V. CHANNEL MODELS FOR CHANNEL STATIC ANTENNAS

The performed measurements suggest that channels can indeed be kept static with antenna counter-movements. The channel at subsequent positions of the device continues to be channel from the initial position where the counter-movement was started. This channel remains until the antenna can no longer keep it static due to technological constraints. In the investigated scheme the antenna is constrained in its counter-movements by the size of the device. Based on the measurements in Sec. III the following channel models are proposed.

As the simplest model

$$H(n) = H(n_0) \tag{1}$$

is considered, where $H(n)$ is the channel at device distance n from an initial position and $H(n_0)$ is the channel at the initial position n_0 where the channel is kept static. $H(n_0)$ can be the physical channel that forms in the environment, it can be an estimate of the channel [2], it can be drawn from a distribution [33] or obtained from a channel model [34], [35].

Instead of a spatial formulation, the model can be formulated in the temporal domain as

$$H(t) = H(t_0) \tag{2}$$

where $H(t)$ is the channel at time t and $H(t_0)$ is the channel at time t_0 when the antenna started to keep the channel static.

In many applications it will be suitable to modify the initial channel $H(n_0)$ with some function F:

$$H(n) = F\left(H(n_0)\right). \tag{3}$$

The function F might add noise, consider estimation uncertainty or model a technological process that is used to keep the channel static, e.g. the influence of moving a device in the near-field of an antenna.

The following model is proposed based on the measurements of physical movement compensation in office environments in Sec. III:

$$H(n) = H(n_0) + Z(n). \tag{4}$$

$H(n_0)$ is the channel at the initial position n_0 at which the channel is kept static. $H(n_0)$ becomes the mean of the channel, as can be seen in Figs. 10c and 10f. Its value is kept for the whole static interval. The residual changes are modelled by a zero-mean random variable Z that is drawn for each n, but its variance is kept during a whole static interval. The model can be used for both the amplitude and the phase, when the variance values for Z are taken from the respective columns in Tabs. 1 or 2. The resulting model is stationary within an interval [36] as the channel statistics remain the same during a compensation interval. From a model viewpoint, the physical compensation with channel static antennas converts a stationary channel (such as in the office environment) into a channel that is piecewise stationary, but with the benefit that the variance is decreased by several orders of magnitude.

VI. CONCLUSION AND OUTLOOK

A technique was investigated that keeps wireless communication channels static under device movements by performing counter-movements of the antenna. Feasibility of the concept for mobile applications was demonstrated with measurements in anechoic and office environments. The performance of channel static antennas was assessed numerically and the size limitations of mobile devices were considered. In such applications, channel static antennas are able to keep the channel piecewise static. Mathematical models for channel static antennas were derived from the measurement results.

It was found that in an office environment the technique can reduce the large fluctuations in the receive power (>30 dB) from small scale fading down to peak values smaller than 3 dB. While the phase shifts for regular antennas increase with increasing distance, the phase shifts were kept static by the counter-movements with residual changes smaller than 10°.

The technique is purely based on the device's movement and size, the antenna does not require channel knowledge to perform the counter-movements. Modern vehicles and smart phones are already equipped with sensors that measure position, speed and acceleration.

Device specific influences on the investigated method need to be assessed, which as a prerequisite requires application driven antenna designs. People and objects that move through the environment are expected to create channel changes that can not be compensated by the investigated technique. On the other hand, the residual changes in the presented measurements are caused by the protruding movement unit, which would not be needed in device specific designs. Performance in other environments and applications also require further investigation.

Channel static antennas might allow a separation of wireless communication channels by their cause, i.e. changes that are caused by platform movement and channel changes that are caused by the environment, e.g. for vehicular channels [37].

This work suggests that Doppler shift [26] is not an intrinsic property of vehicular channels [37], but that it can be compensated.

CONFLICT OF INTEREST

Technische Universität Wien, Vienna, Austria, the author's employer at the time of invention, has filed a patent [38].

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