Characterization System for Radio Channel of Adaptive Array Antennas

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ABSTRACT

This paper describes a multichannel measurement system for the analysis of the radio channel of adaptive array antennas. It provides real-time recording of signals from multiple input channels. Due to this multielement reception, the incidence angles of the received signal components can be resolved. Wideband sounding provides the delay information. This allows the characterization of the two-dimensional radio channel of adaptive antenna systems in realistic environments. The system is based on a complex wideband radio channel sounder and a fast RF switch. As an example, the system allows measuring of complex impulse responses for a 16-element array with 17 ns delay resolution, and a delay range of 4.3 µs for 26 m/s mobile speed. The continuously recorded path lengths can be over one hundred meters. Practical channel measurements have been performed with a linear array of 8 elements. In these measurements the received signal components could be separated with 13° angular and 20 ns delay resolution. The developed method provides a novel approach to the two-dimensional analysis of the mobile environment.

1 INTRODUCTION

The need for mobile telecommunication is increasing rapidly and the existing systems are meeting their capacity limits. Reducing cell sizes and building additional cell sites and base stations is time consuming and expensive. This has lead to a search for new system solutions capable of serving the growing number of users. One interesting candidate is the spatial separation of users by the employment of adaptive antennas at the base stations of networks. The implementation of adaptive BS antennas in difficult multipath environments requires knowledge of the radio channel. This fact has been widely acknowledged and attention has been paid to measuring the properties of the channel, including directions-of-arrival (DOAs) and time delays of different multipath components. The delays of different multipaths can be resolved using a wideband channel sounder. A conventional method for measuring the DOAs of the signals is to rotate a narrow-beam antenna [1]. This gives very good angular resolution provided that the effect of the antenna pattern is removed from the results. Another technique is to simulate an array antenna by moving a single antenna consecutively to various positions in a rectangular or circular grid [2,3]. The DOAs can be determined from the measured phase differences of the signals received at different positions. The advantage of this method is that the mutual coupling in the array is avoided. Both of these methods are however slow and require a static channel. Also array systems using simultaneous reception from multiple channels have been presented [4]. This kind of systems are the most realistic ones but also very complex and expensive due to the large number of receivers required. They also require accurate calibration procedures to compensate for the phase and amplitude mismatches between channels. In this paper we describe a multichannel measurement system using a single receiver. The system is based on a complex wideband radio channel sounder [5] and a fast RF switch. It provides real-time recording of signals from multiple input channels and thus enables real dynamic array measurements of the radio channel of a moving mobile. The continuously recorded path lengths can be over one hundred meters. Except of being fast, this method is also realistic in a sense that it simulates a real adaptive array and therefore gives a realistic picture of the operation of radio systems employing adaptive antennas in practical environments. The data produced by the system can be utilized e.g. in antenna development, adaptive algorithm simulations, and channel modeling. In this paper the system is described and its functionality demonstrated with measurements of practical channels.

2 DESCRIPTION OF SYSTEM

The measurement system [6] is based on the complex wideband radio channel sounder developed at Institute of Radio Communications (IRC), Helsinki University of Technology (HUT) [5]. The carrier frequency of the sounder is 2.154 GHz and the bandwidth is 100 MHz. The sounder consists of a transmitter and a receiver synchronized by accurate 10 MHz rubidium standards to gain good phase stability. It produces the complex impulse response (IR) of the radio channel by correlating the received signal with a replica of the transmitted PN-modulated signal. The correlation is performed either by hardware in the sliding correlator, or the received and demodulated signal is sampled directly and the correlation is calculated with post processing [5].

In order to measure multiple antenna elements with a single receiver, a fast RF switching unit is required behind the antenna. The used switching unit is based on a TTLcontrolled GaAs switch (Mini-Circuits VSWA 2-50 DR) with a switching time of 3 ns. The system used in this paper has 8 channels. Figure 1 shows a schematic diagram of the measurement system.

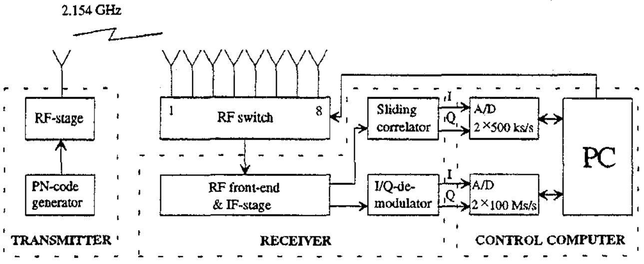


Figure 1. Measurement system.

During the channel measurements the transmitter of the sounder is moved around, and the array simulating a BS antenna is connected to the receiver. The angular distribution of the received signal components can be solved by comparing the relative phases of the element signals. The dynamic mobile environment causes phase rotation between IRs measured from subsequent elements. Typically, the phase rotation is not linear and can not be separated from the phase difference that depends on the DOA of the signal. The maximum possible phase shift between two array elements in an N-element array is

$$\Delta\phi_{\max} = \frac{f_{D,\max}}{f_m \cdot N} \cdot 360^\circ \tag{1}$$

where f_m is the rate of measuring IRs from the whole array and $f_{D,\max}$ is the maximum Doppler frequency. Thus, the required measurement rate depends on the desired directional accuracy and the maximum mobile speed. The desired directional accuracy depends on the beamwidth of the array. For example, if the maximum allowed beam mispointing is 10 % of the 3 dB beamwidth of the array at broadside, the maximum phase rotation between two elements of an 8-element $\lambda/2$-spaced linear array is 4.6°.

The sliding correlator detector of the used system limits the measurement rate to 24 IR/s corresponding to 3 IR/s for the whole array of 8 elements. Thus array measurements are only possible in static environments. Instead, direct sampling provides fast recording of IRs and allows measurements also in dynamic environments. As an example, Table 1 presents the delay resolution $\tau_{\min}$, delay range $\tau_{\max}$, and the corresponding maximum mobile speed $v_{\max}$ and resulting continuous path length for a given system configuration in the direct sampling receiver. The continuous path length is limited by the memory buffer of the measurement device (4 Mbytes). A 16-element linear array with $\lambda/2$ spacing is considered and the criterion for directional accuracy is 10 % of the 3 dB beamwidth at broadside.

In Table 1 f_c is the chip frequency and L_c the length of the modulating PN-code in the transmitter. Before calculating the mobile speed the measurement frequency in Eq. (1) was divided by three because the system does not provide absolute delays and 3 successive IRs have to be sampled to compensate for the timing errors. As shown in Table 1, the maximum mobile speeds can be very high. The corresponding delay ranges are, however, infeasibly short. The practical path lengths are of the order of 20 - 50 meters.

Table 1. Delay resolution, delay range, and corresponding maximum mobile speed and continuous path length with direct sampling.

f_c [MHz]	L_c [bits]	$\tau_{\min}$ [ns]	$\tau_{\max}$ [µs]	$v_{\max}$ [m/s]	s_{max} [m]
2.5	31-255	400	12-102	22 - 2.7	187 - 23
10	31-1023	100	3.1-102	88- 2.7	187 - 5.7
30	31-2047	33.3	1.0-68	265 - 4.0	187 - 2.8
60	31-2047	16.7	0.5-34	531 - 8.0	187 - 2.8

3 MEASUREMENTS

The measurements presented in this paper were performed with the sliding correlator receiver. The nominal delay resolution was 18.6 ns, and the used PN-code and sampling rate resulted in a delay range of 1.9 µs. The prototype antenna array used in the measurements was an 8-element linear array of probe-fed short-circuited quarter-wave microstrip patches with air substrate. The element spacing was $\lambda/2$ and the polarization was vertical. The elements were connected to the switching unit by semi-rigid coaxial cables. The array and the switch were both mounted on an aluminum support. Figure 2 presents the configuration. The switching unit and the semi-rigid coaxial feed cables can be seen behind the array.

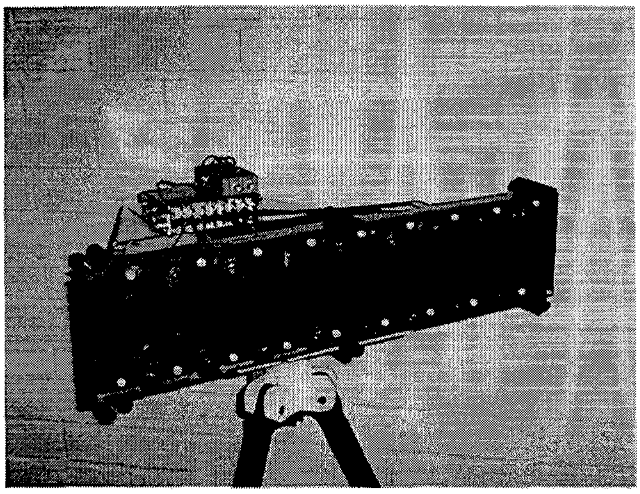


Figure 2. Prototype array used in the measurements.

The complex IR $x_n(\tau)$ corresponding to element n (τ is the excess delay) was sampled and recorded from the output of the sliding correlator. The transmission loss and change of phase in the feed cables and the switching unit were removed from the results. This was done by multiplying $x_n(\tau)$ by the inverse of the common transmission parameter c_n of the two components, measured at the center frequency. The resulting corrected IR $s_n(\tau)$ contains the amplitude level $a_n(\tau)$ and phase $\delta_n(\tau)$

$$s_n(\tau) = c_n^{-1} \cdot x_n(\tau) = a_n(\tau) e^{j\delta_n(\tau)} \tag{2}$$

The corrected IRs from each element were weighted by amplitude coefficients w_n to obtain lower sidelobes. If no weighting was used, the sidelobes would be only 13 dB below the peak of the main beam and weak signals would be difficult to resolve. On the other hand, the 3 dB beamwidth without weighting would be the smallest possible that can be achieved with a 4 λ long array (13° at broadside). Chebyshev amplitude tapering for -25 dB nominal sidelobe level was used. The resulting maximum sidelobe level was, however, only about -20 dB due to nonidealities in the antenna and its feed network. The chosen tapering is a compromise between the lower sidelobes and the narrower beam. At broadside direction the resulting 3 dB beamwidth is about 15°. At 60° scan it is approximately 39° and the beam covers the sector from 47° up to 86°. Therefore, the signals received above ±60° are not reliable. To estimate the DOAs the angular signal distributions at each delay point of the measured IRs were calculated as

$$S(\theta,\tau) = \sum_{n=0}^{N-1} w_n s_n(\tau) e^{j(nkd\sin\theta - \delta_0(\tau))}$$

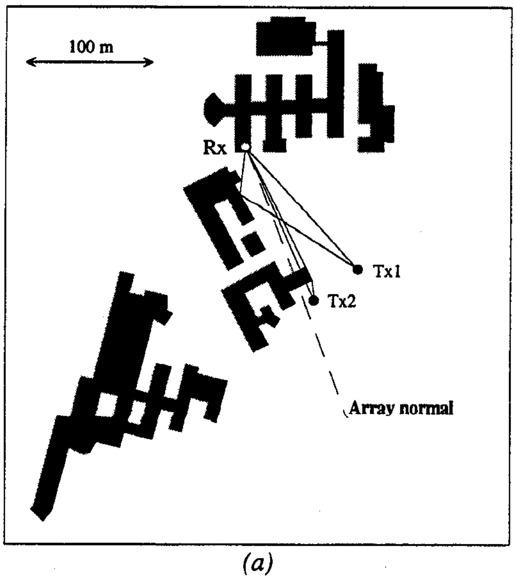
$$\Rightarrow S(\theta,\tau) = \sum_{n=0}^{N-1} w_n a_n(\tau) e^{j(nkd\sin\theta + \varphi_n(\tau))},$$

$$\varphi_n(\tau) = \delta_n(\tau) - \delta_0(\tau) \tag{3}$$

where $\varphi_n(\tau)$ is the phase relative to the first element. Angle θ was swept from -90° to 90°, where $\theta = 0$ corresponds to the array broadside direction. The maximum value of $S(\theta,\tau)$ at each delay point occurs when the phase relative to the first element is

$$\varphi_n(\tau) = -nkd\sin(\theta_0(\tau)), \qquad n = 0 \ldots N-1 \tag{4}$$

where $\theta_0(\tau)$ is the direction of the received signal component corresponding to time delay of τ.



(a)

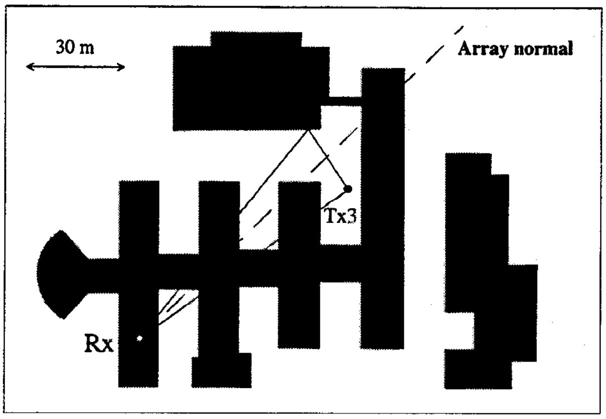
Channel measurements were performed in both suburban and urban environments. The suburban measurements were carried out in the campus area of HUT in Otaniemi, Espoo, Finland. The urban measurements were performed in the city center of Helsinki, Finland.

A. Suburban environment

During the suburban channel measurements the receiving array was located on the roof of the main building of the Department of Electrical and Communications Engineering, approximately 10 meters above ground level. The discone antenna that was used in the transmitter was placed on top of a 2-meter high pole that was then positioned in 3 different locations (Tx1-Tx3) within the range of a few hundred meters. The transmitter power level was 24 dBm. The environment type in the campus area is typical suburban. The buildings have a maximum of 3 stories, and their surroundings consists mainly of lawns and small forest areas. Due to the slow measurement rate of the sliding correlator receiver, only two consequent IRs were averaged from each element during one sweep over the array. The self noise of the sliding correlator [7] was cut out from the results with a threshold of 25 dB below the peak of the strongest signal component. The transmitter and receiver locations together with the strongest signal paths are presented in Figure 3. A short description of the propagation environment and the distance from the transmitter to the receiver at different transmitter locations is given in Table 2.

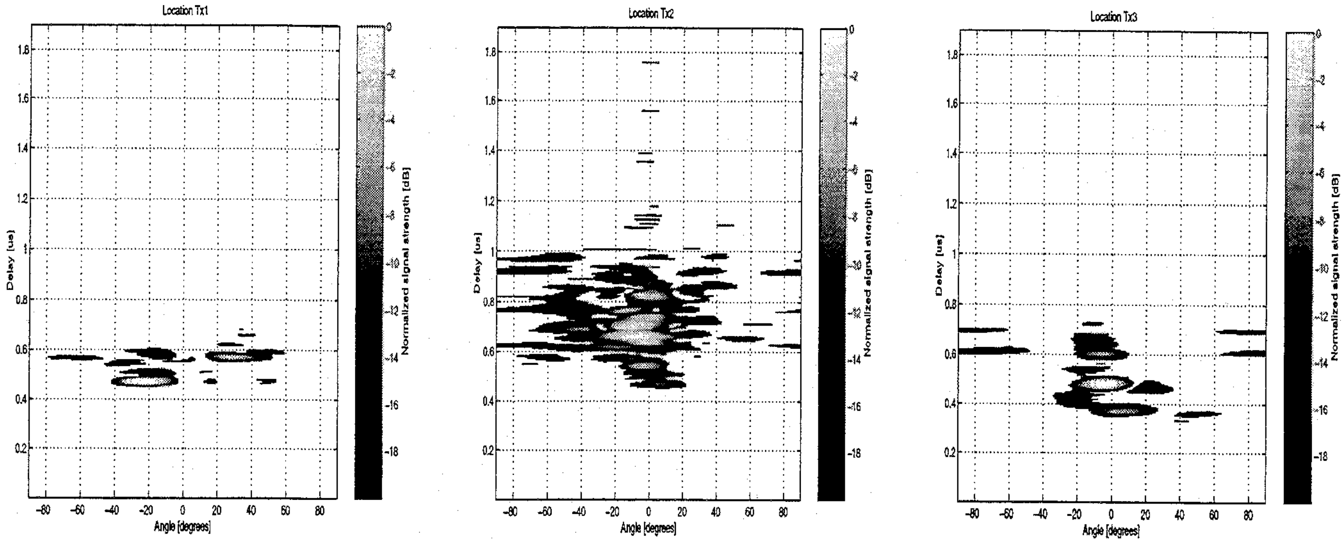
Table 2. Description of transmitter locations in suburban channel measurements.

Location	Description	Distance
Tx1	LOS. 3-story building at left.	140 m
Tx2	No LOS. Behind the corner of a 2-story building.	140 m
Tx3	No LOS. High building at right.	80 m



(b)

Figure 3. Transmitter and receiver locations and strongest signal paths in suburban channel measurements. (a) Locations Tx1 and Tx2. (b) Location Tx3.



(a) (b) (c)

Figure 4. Measured angle and delay distributions of received signals in suburban channel measurements.

The measured signals for various transmitter locations are shown in Figures 4 (a) - (c). The horizontal axis is the azimuth angle θ seen at the receiving array. The vertical axis is the time delay of the received signal component (τ). Because the system does not provide the absolute delays, the delays have been corrected to match the real situation. The maximum delay of 1.9 µs corresponds to 570 meters. The sidelobes have been cut out from the results (with threshold of -20 dB below the main signal peak) to obtain clear pictures. Because of the relatively wide beam of the Chebyshev-weighted 8-element array, the signals look like horizontal lines. This limits the accuracy of resolving the DOAs. The delay resolution can be seen to be approximately 20 ns, which matches with the theoretical value (18.6 ns).

In location Tx1, Fig. 4 (a), the reflection from the building at left from the transmitter is clearly seen (the component at +27°). The reflected signal is about 5 dB weaker than the direct component. The delay between the direct and reflected component is approximately 100 ns which corresponds to 30 meters. In addition, there is a weak back reflection component. In location Tx2, Fig. 4 (b), the situation can be seen to be more complex. The delay spread is large and several signal paths exist. The possible propagation paths contain e.g. the wall and roof-top diffraction from the building obstructing the direct path. In location Tx3, Fig. 4 (c) the reflection from the wall at -6° is 10 dB stronger than the first component propagated through a roof-top diffraction or directly through the building.

B. Urban environment

The urban channel measurements were performed at night to assure time stability of the channel. The receiving array was placed on the roof-top of a car approximately 4 meters above ground level. The car was parked on the sidewalk of the street downtown Helsinki. The distance to the nearest wall was 3 meters. Also in this case the transmitter antenna was placed on top of a 2-meter high pole positioned in 3 different locations (Tx4-Tx6). The transmitter power level was 40 dBm. The environment type was urban with typical building height of 7 stories. Ten consequent IRs were averaged from each element. To obtain full 360° azimuth coverage, the measurement in each transmitter location was performed in six 60° sectors and the sectors were combined with post processing. The self noise of the sliding correlator was again removed from the measurement results.

A map presenting the transmitter and receiver locations during the measurements is shown in Figure 5. Description of the transmitter locations is given in Table 3. Figure 5 also shows the six measured sectors. The origin of the used coordinate system points left along Aleksanterinkatu (see Fig. 5) and the angle values increase clockwise. The measured signals for various transmitter locations are shown in Figures 6 (a) - (c). The delay values increase towards the edges of the figures. The delays have been corrected to match with the physical situation in locations Tx4 and Tx5. In location Tx6 the delays are difficult to correct due to the unknown signal paths.

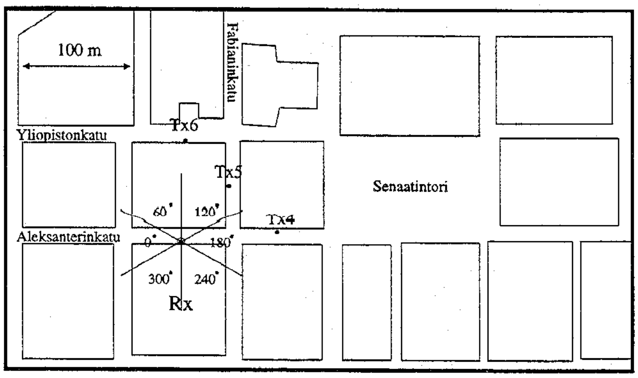
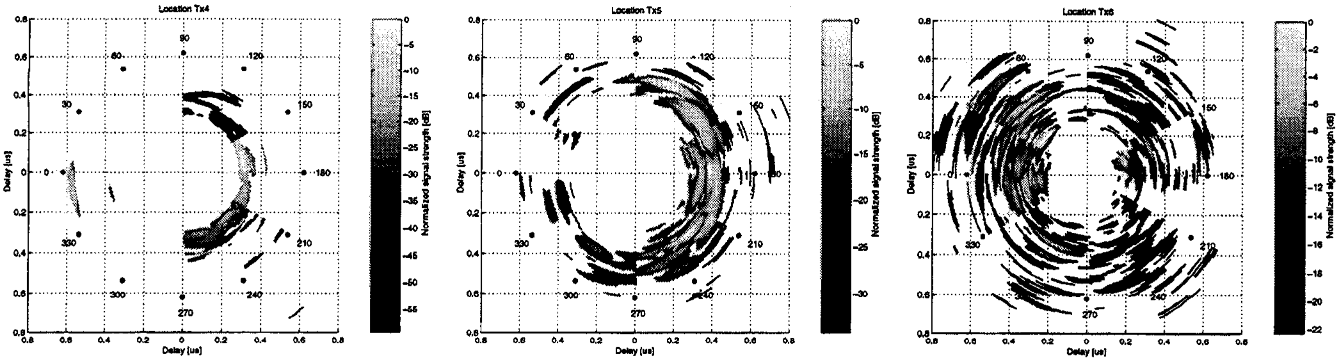


Figure 5. Transmitter and receiver locations in urban channel measurements.



(a) (b) (c)

Figure 6. Measured angle and delay distributions of received signals in urban channel measurements.

Table 3. Description of transmitter locations in urban channel measurements.

Location	Description
Tx4	On the northern side of Aleksanterinkatu. Distance from nearest wall app. 3 m. LOS.
Tx5	On the western side of Fabianinkatu behind one block corner. 2 m from wall. No LOS.
Tx6	On the southern side of Yliopistonkatu. One block between transmitter and receiver. 3 m from wall. No LOS.

In location Tx4, Fig. 6 (a), the LOS component is clearly dominant. Both the angular and delay spread of the signal are small. In location Tx5, Fig. 6 (b), where the transmitter is behind one corner of a block, the situation is already much more complex. The first component is diffracted from the corner of the block at 160°. The reflections from the walls on both sides of Aleksanterinkatu are clearly seen in the figure. In location Tx6, Fig. 6 (c), there was a whole block between the transmitter and receiver. The main part of the signal is now coming from the angular sector between 330° and 60°. This is interesting because the geometry of the streets in this side does not differ considerably from that in the other side, where there are only two stronger signal components. The angular spread of the signal is now very large and signal components exist in almost all azimuth directions. Only in the direction of the direct path through the block there seems to be no signal.

4 CONCLUSIONS

The system presented in this paper allows the separation of the received signal components with different time delays and DOAs. The measured directional and delay signal profiles match well with the real situations. The angular resolution of the system depends on the size of the used array. The best resolution achieved with the used 4 λ long linear array is approximately 13°. The delay resolution in the measurements was 20 ns. The main problem with the current setup is that the sliding correlator receiver allows only static measurements. Dynamic measurements will be performed in the next phase of the project with the direct sampling receiver. The system will also be extended for larger arrays with independent reception of two polarizations. The developed system allows fast real-time recording of signals from different antenna arrays and radio channels and thus enables real dynamic array measurements of the radio channel of a moving mobile. The continuously recorded path lengths can be over one hundred meters. The presented method provides a novel approach to the two-dimensional analysis of the mobile environment. The data produced by the system can be used e.g. in antenna development, dynamic adaptive algorithm simulations, and channel modeling. The signals themselves can be used directly as an input to a simulator, or alternatively channel models can be developed and used in simulators. Situations of multiple moving users can be simulated by combining the data recorded from several paths.

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