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Downlink Calibration Requirements for the TSUNAMI (II) Adaptive Antenna Testbed.

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ABSTRACT

The TSUNAMI (II) project is an investigation into the use of Adaptive Antenna Technology. The field trial system has been developed for the purposes of investigating the feasibility of implementing such a system using a GSM-1800 base station system. The field trial system uses a digital baseband beamforming technique (DBF) which, like all DBF systems, relies on the accurate transfer of weighted signals to and from the antenna array elements. As such, an accurate and reliable calibration system is required to combat effects such as temperature and humidity on the individual antenna array paths. In this paper, are present results of studies made on the field trial system, with regard to the operational temperature variations over an extended period of time. Investigations are presented of the TSUNAMI (II) downlink calibration technique and the implications for future adaptive antenna array calibration systems.

I. THE TSUNAMI (II) PROJECT

The TSUNAMI (II) (Technology in Smart antennas for UNiversal Advanced Mobile Infrastructure - Part 2) project has been set-up under the EU ACTS research programme and is the extension of the RACE TSUNAMI project [1]. The project is an investigation into the use of adaptive antenna systems for future generation cellular networks. The key aims of the project are to demonstrate the capacity increase and coverage extension [2] that can be gained through the use of spatial diversity in an Adaptive Antenna Base Station Subsystem (AA-BSS) in a mixed cell environment.

The adaptive antenna system operates via filtering in the spatial domain, through modification of the transmitted or received antenna array signals with respect to time, frequency and spatial response. This is accomplished by means of amplitude and phase weightings applied to the transmitted signals at digital baseband. These signals are then upconverted in quadrature and applied across the array [3].

Application of various digital beamforming algorithms on these weights allows a narrow beam pattern to be produced from the adaptive array. This beam can be steered towards or *track* a desired user and hence reduce the intercell interference levels within the cellular system, compared with that of an omnidirectional or sectored base station system. In addition, spatial

nulls can be introduced into the same beam pattern towards strong sources of interference, or unwanted users occupying the same channel bandwidth. Alternatively, these sources of interference may be secondary users of the same system, such as in the case of SDMA (Space Division Multiple Access) applications [4], where more than one user may be supported on the same channel, separated spatially through the use of adaptive array processing.

II. REQUIREMENTS ON ADAPTIVE ANTENNA ARRAY SYSTEMS

Previous investigations, through the RACE TSUNAMI project [5], have shown that digital baseband beamforming systems rely on the accurate transfer of the phase and magnitude weightings from the baseband beamformer up to their application across the array elements. Small phase or amplitude errors in these weights, due to time variant distortions in the transceiver chain, can alter the depth and position of these required nulls. Hence, calibration of the complex element weighting factors is crucial for the success of the field trial.

These distortions can arise from small environmental changes such as temperature and humidity, electrical and mechanical variations and even changes in the channel centre frequency and channel gain. These distortions will effectively alter the transfer function of each adaptive antenna path. The study in [5] found that temperature variations, on the antenna alone, over a range of 14 to 27 degrees Centigrade, resulted in mean distortions of 1.76dB magnitude and 180 degrees phase error across an array and hence rendered the beamforming algorithms of little use at these times. Although temperatures are not expected to change over such a wide range during a short time period, it is with a view to the longer-term stability of the system that the active calibration scheme was developed. In an operational adaptive antenna network, it would not be practical to 'off-line' the system and perform a manual calibration (the calibration approach adopted in RACE TSUNAMI).

III. TSUNAMI (II) FIELD TRIAL SYSTEM OVERVIEW

The TSUNAMI (II) field trial system includes a modified DCS-1800 base station system, supplied by Motorola, to which an 8-element adaptive antenna sub-system has been retro-fitted.

Figure 1 shows the overview of the TSUNAMI (II) Downlink base station system.

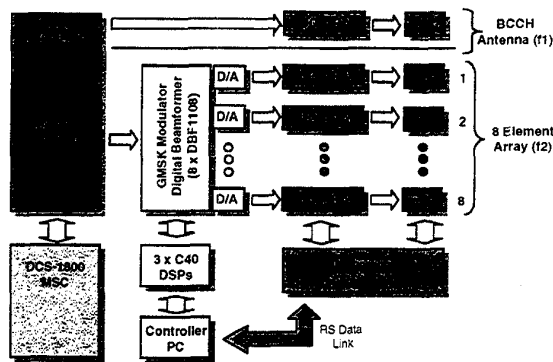


Figure 1: TSUNAMI II Downlink Overview

IV. DOWNLINK CALIBRATION SYSTEM

The TSUNAMI II downlink calibration system was designed to provide an automatic and *transparent* calibration process. Ideally, this would enable the field trial system to provide 30dB post-calibration, spatial isolation between the wanted signal and each interferer in the same channel, for both the uplink and downlink directions. Intuitively, this spatial filtering can only be achieved if the individual paths of that adaptive antenna array have nominally identical transfer functions. In order to attempt to achieve this degree of spatial isolation it was believed, from the studies in [5], that the post-calibration error requirement across the array elements would have to be better than 3 degrees phase and 0.5dB amplitude.

A. Downlink Calibration Technique

Calibration of the transmitter system is not possible through the use of CW signal injection, as has been used in the TSUNAMI (II) receive calibration system [6]. This approach would result in RF tone transmission across the entire network and hence not provide a transparent calibration scheme. Instead, a feedback system utilising the *live* transmitted data has been implemented. Figure 2. shows the outline of this system.

The transmit calibration process takes place during the valid or *in-call* timeslots of the transmitted frame structure. Each branch of the antenna array is sampled in turn, using the masthead injection couplers and a switched combiner network. In addition, a complimentary signal sample is obtained from the baseband digital beamformer output for the appropriate branch. at the time of data transmission. This digital signal comprises 8-samples per bit for each I and Q data symbol.

The RF transmitted signals, sampled at the masthead, are fed down to the calibration system via a 75 metre, low loss cable and downconverted to baseband in quadrature, using local oscillator signals obtained directly from the TSUNAMI AA-BSS. These quadrature signals are sampled using a dual 8-bit

A/D converter, also at 8 samples per transmitted data bit and stored in a buffer (FIFO) until required for processing. The sample clock used is taken directly from the main TSUNAMI II system, to maintain signal phase accuracy.

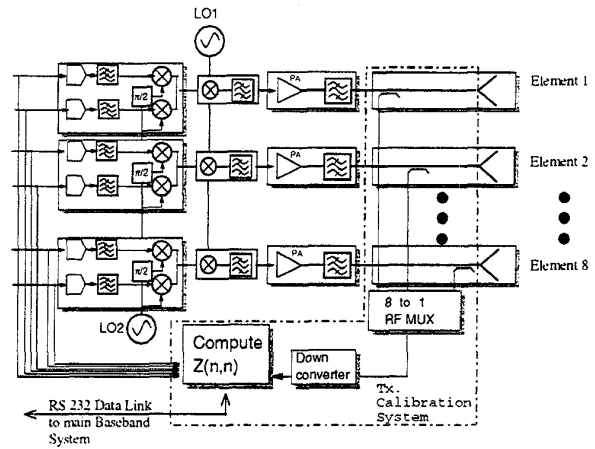


Figure 2: Downlink Calibration System

The stored data from both digital and RF sources are processed to calculate a relative error or *Correction Factor* for each array path. These Correction Factors can be applied to the appropriate beamformer output weights, at digital baseband, to compensate for the present distortions in the transmitter chain.

Currently, the system operates on a continuous calibration mode. Storing the *last valid calibration Correction Factor* calculated. This value is only used to update the main AA-BSS system on request, through the RS-232 link.

B. Downlink Beamformer Weight Correction Factor Calculation

Digital Signal Processing (DSP) of the stored data is performed using a TMS320C50 processor. With reference to Figure 3, $F_i(t)$, $G_i(t)$ and $H_i(t)$, represent the forward path transmitted data, analogue sampled path transmitted data and the baseband digitally sampled data respectively, where i represents the transmission path or array element number (1..8).

$X_i(t-\tau)$ represents the baseband digital output in quadrature (8-bit I and 8-bit Q data) of the beamforming network in the AA-BSS, where τ represents the time delay between the data becoming available at this output, to the time taken to sample the transmitted data from the RF analogue path. $Y_i(t)$ is the transfer function from the FIFO storage of the transmitted data signal to the DSP.

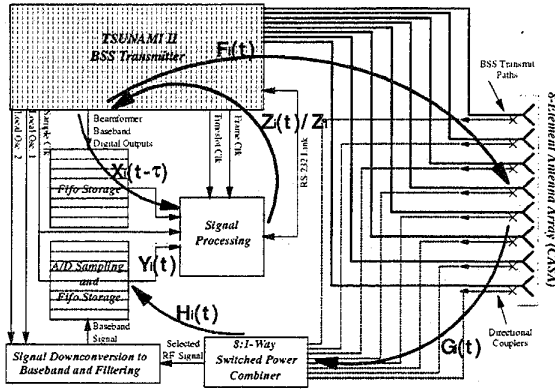


Figure 3.: Downlink Calibration Technique

Using the above definitions of the transmitter calibration loop and taking into account the time alignment of the sampled signals, the transfer function of the calibration system $Z_i(t)$, for an adaptive antenna element i at time t , can be expressed as:

$$Z_i(t) = \frac{Y_i(t)}{X_i(t)} = \frac{Y_i(t)X_i(t)^*}{|X_i(t)|^2} \quad (1)$$

where:

$X_i(t)^*$ - denotes the complex conjugate of $X_i(t)$.

$|X_i(t)|^2$ - represents the square of the modulus of $X_i(t)$.

From analysis of the calibration loop, this may also be expressed as:

$$Z_i(t) = F_i(t)G_i(t)H_i(t) \quad (2)$$

Some assumptions are now be made about the calibration loop:

1. The electrical characteristics of the calibration paths from the injection couplers to the switched power combiner ($G_i(t)$) can be accounted for and are invariant over the measurement sample periods, i.e. These parts of the system can be characterised at the start of field trial and are not expected to change value, relative to the variations in the forward/uplink path of the system.
2. Assumption 1. applies for all the common signal paths ($H_i(t)$).
3. The local oscillators run continuously and do not introduce any phase offsets/clock skew into the calibration system.
4. The sampled data can be time-aligned with the baseband digital beamformer weights.
5. The calibration process removes the modulation scheme.

Following these assumptions, Equation 2 now becomes:

$$Z_i(t) = F_iGH = Z_i \quad (3)$$

Hence, the relative *Correction Factor* over the calibration measurement period, referenced to element 1 of the array, can be expressed as:

$$CorrectionFactor = \frac{Z_i}{Z_1} = \frac{F_i}{F_1} \quad (4)$$

Equation 1 and Equation 4 now show that the calibration technique, under the assumptions stated, will yield the appropriate *Correction Factor* to be applied to the beamformer weights, to adjust for forward path electrical variations. Hence, the calibration scheme should provide for reliable operation of the AA-BSS, if applied regularly enough to counter the rate of change of the electrical path variations.

V. CALIBRATION INTEGRATION RESULTS

As part of the TSUNAMI (II) field trial system integration process, the calibration unit was used to study the functionality and performance of the basestation system.

A. Temperature Variation Study

In this study, the field trial downlink system was left running for extended periods on a fixed beampattern, with the calibration system operating open loop. In this way it was possible to record the drifts in the amplitude and phase of the transfer function for each of the electrical paths of the 8-element array. Over the same data acquisition period, the indoor (basestation / field trial radio room) and outdoor (antenna mast / array) air temperatures were logged. This data was then used to study the behaviour of the field trial system.

Figure 4. shows the amplitude and phase variation of the transfer functions for each of the 8-elements. The information has been logged continuously over a period of 4 days, at one minute intervals. Also shown, are the temperature variations over the same measurement period and interval. Note that the transfer functions have been normalised with respect to a single array element path (No.1) and to their initial values at time $t = 0.0$ hours. Hence the plots demonstrate the relative drift of each of these parameters over time.

Over the period investigated, temperature variations in both the outdoor and indoor environment can be observed. Initial variations of the radio room temperature are largely due to the heating effects of the AA-BTS transceiver units *warming-up* and heating the surrounding air of the enclosed room. After this period, the radio room temperature settles to an ambient temperature of around 41 degrees Centigrade, with a small fluctuation (± 1 degrees Centigrade) due to air-conditioning units positioned in rooms adjacent to the radio equipment room. Outdoor temperatures are affected only by local weather conditions over the measurement period i.e. these show the air temperature drop overnight and increase during the day, with values typical for the time of year. These temperatures fluctuated between 11 and 25 degrees Centigrade. Note that in

each case it is the localised "still" air temperatures that are logged and not the actual equipment temperatures.

Over the measurement period, variations in the transfer functions of the array paths can be detected. Some of these variations are exaggerated by the normalisation technique used on the data i.e. a change in the transfer function of array path No.1, the reference path, is reflected in the plotted responses of all of the other paths.

The variability of these transfer functions can be put down to a wide variety of temperature related factors, not directly measurable (or avoidable) at the time of the investigations e.g. connector expansion, signal cable extension, component drift, etc. It is also worth noting that the measured temperature of the air may not be directly related to the actual temperature of the subsystem units / internal components at the point of measurement. A time lag or lead will be present depending on the source of the temperature change. Measurement on each component of the field trial system was not the intention nor a practical proposition for the investigations conducted.

B. Simulated Minimum Calibration Requirements

In order to further study the effects of the measured variations in the array path transfer functions on the requirements of the calibration scheme, a simple simulation was performed. The constraints of the simulation were those of the TSUNAMI (II) calibration specification: 3 degrees maximum phase error or 0.5 dB maximum amplitude error across the array. At each occasion that either of these constraints was about to be exceeded, this data point was used as a *calibration* point. The values of the transfer functions were used to reset the array statistics at this point - as if a real (and ideal) calibration had taken place. The analysis then continues with this value until the next point that exceeds the constraint, or until the end of the data log.

In Figure 5 are shown results of this simulation. The plots show the resultant relative drift in array path transfer function amplitude and phase respectively, over the full time period of the Temperature Variation Study. Each registered *calibration* point is indicated by a 'X', the position of which indicates whether the *calibration* occurred due to either an excess of amplitude or phase encountered during the simulation process.

The results of the simulation show a total of 55 calibrations required to maintain the phase and amplitude within the bounds of the specification: 49 due to an excess amplitude, 6 due to an excess of phase. Over the 96 hour period, 7 calibrations were required within 1 minute (occurring between 14 hours and 83 hours) and the maximum time between calibrations was 1086 minutes (18.1 hours). As a result, it can be seen that despite long periods of relative stability in the array paths existing, they are not necessarily consistent or repeatable. Hence, any practical calibration method would be required to make corrections for these drifts in less than 1 minute, to allow for electrical

variations of the array paths and ensure adequate beamformer performance. Such a system is already in operation in the TSUNAMI (II) field trial system, which is capable of performing a calibration correction factor calculation every 8 frames or approximately every 37 milliseconds, if required.

VI. CONCLUSIONS

The successful integration and operation of this equipment in the field trial has been a major success for the TSUNAMI (II) project.

The investigations in this paper have demonstrated the effects of the variation of the operational temperatures on the performance of the downlink array paths over an extended period of time.

The data obtained from these studies has been used in a simulation of the minimum requirements on the calibration subsystem to maintain the performance of the array within the specification defined for the TSUNAMI (II) field trial system. The results of this investigation have indicated that a single calibration at the start of operation of an AA-BTS would not be sufficient for reliable operation of that system, over both short and longer term operation. Further, that a continuous (active) calibration system would be required to maintain adequate operation of the AA-BTS under the conditions experienced.

VII. ACKNOWLEDGEMENTS

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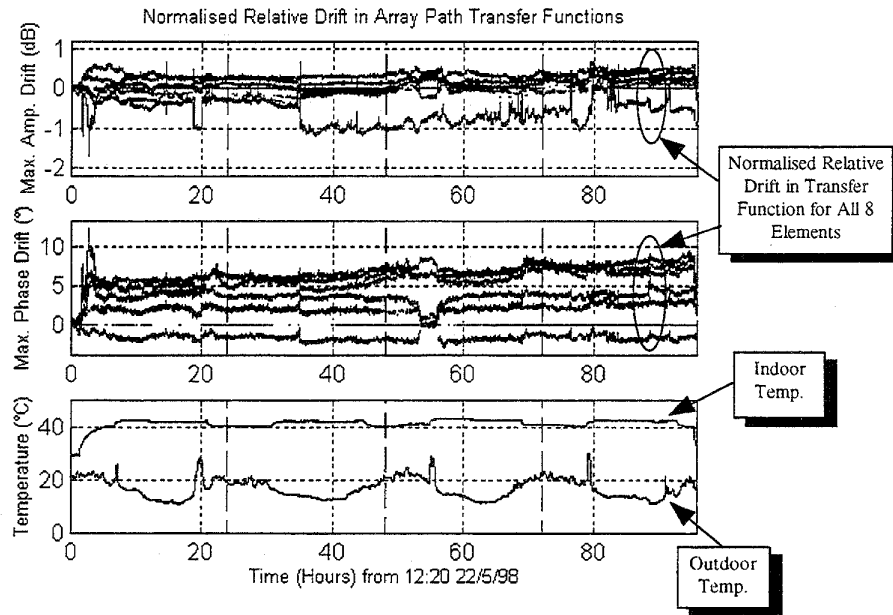


Figure 4: Typical Drift in Array Element Transfer Function and Temperature Variation over Time

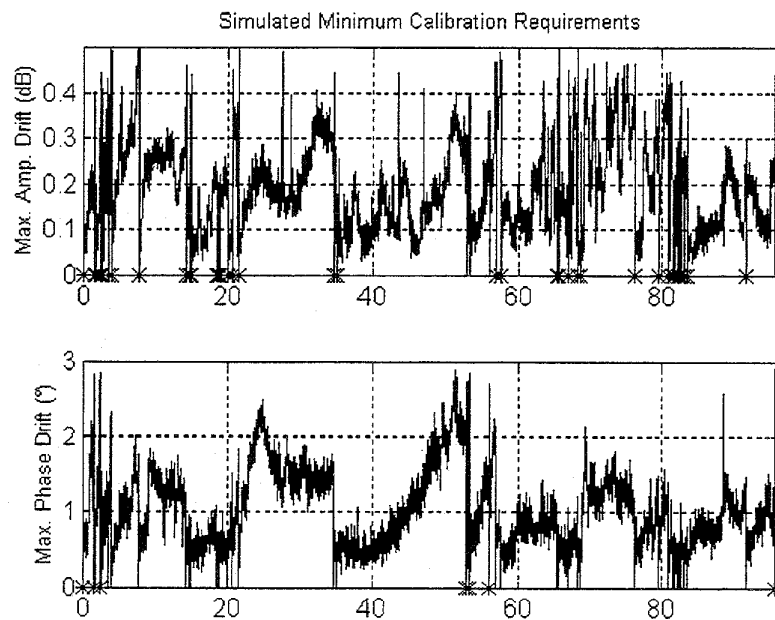


Figure 5: Array Element Transfer Function Drift under Simulated Calibration.