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Wireless Cable Method for High-order MIMO Terminals Based on Particle Swarm Optimization Algorithm

Wei Fan, Fengchun Zhang, Pekka Kyösti, Lassi Hentilä, and Gert F. Pedersen

Abstract—Conducted cable setups have been dominantly utilized in the industry for performance testing of multiple-input multiple-output (MIMO) terminals. The wireless cable method, which can achieve cable connection functionality without actual radio frequency (RF) cable connections, is a promising alternative. To date, the wireless method has been only discussed for 2×2 MIMO terminals in the literature. However, the algorithm is not directly applicable for high-order MIMO terminals, due to the high computation complexity to determine the calibration matrix and high system cost to implement the calibration matrix. In this paper, an efficient particle swarm optimization (PSO) algorithm is proposed to determine the calibration matrix for high order MIMO systems. Furthermore, a novel implementation of the calibration matrix in the radio channel emulator (CE) is proposed, which can significantly reduce the system cost. To validate the proposed algorithm, two MIMO mockups, each equipped with four antennas, were measured in an anechoic chamber. The measured results demonstrated the effectiveness of the PSO algorithm to establish wireless cable connections for 4×4 MIMO terminals.

Index Terms—particle swarm optimization algorithm, MIMO performance testing, wireless cable method, MIMO over-the-air testing, radio channel propagation

I. INTRODUCTION

The utilization of multiple-input multiple-output (MIMO) systems in wireless radios is pervading in long-term evolution (LTE) and IEEE 802.11 technologies [1]. Accessible connectors are typically available for the purpose of conducted testing. In this way, built-in antennas can be detached from connectors and RF test signals can be carried to the device under test (DUT) antenna ports directly with RF cables, bypassing the built-in antennas. The conducted testing has been dominantly utilized in the industry, due to its simplicity and low-cost [2]. However, it presents many drawbacks, such as opening of terminal case, possible lack of antenna connectors, and non-idealities introduced by RF cable connections [2]–[4]. Radiated testing, where built-in antennas are used directly as the interface to receive/transmit test signals, is highly attractive [2], [5], [6]. The key challenge in the radiated testing is how to guide specified testing signals to DUT antenna ports in a controllable manner without distortions.

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Works on radiated testing can be categorized in two different directions, i.e., radio channel emulation and wireless cable method [3]–[13]. The objective of radio channel emulation method is to characterize the complete end-to-end performance of the DUT, via physically reproducing RF multipath environments in laboratory conditions. The RF performance of user equipment (UE) offered by multi-antenna techniques can be evaluated in the emulated fields with device untouched [2], [5]–[8]. OTA methods, either a costly multi-probe anechoic chamber (MPAC) method that offers a full control of emulated fields or a mode-stirrer reverberation chamber (RC) method which has a limited channel emulation flexibility, have been intensively discussed in the industry and academia [6], [11], [12]. A reconfigurable RC equipped with antennas connected to transmitting sources and reconfigurable impedance elements was proposed in [9], [10] as another alternative. The MPAC method is a popular candidate for end-to-end performance testing of MIMO terminals. However, a major drawback of the MPAC method is its high setup cost, especially when the test objects are large (such as high-order MIMO systems) or three dimensional (3D) radio channel emulation is required [14].

The objective of the wireless cable method is simply to guide specified test signals to the DUT antenna ports over-the-air (i.e. virtual RF cable connection) [3], [4], [13], [15]. The wireless cable method is highly attractive for DUTs equipped with a number of antennas, such as LTE UEs and automobile systems, since the required number of OTA antennas is only determined by the number of DUT antennas, regardless of the channel models and test object size [3], [4]. The basic idea of the wireless cable method is to implement a calibration matrix in the channel emulator (CE) to compensate the transfer matrix between the OTA antenna ports and DUT antenna ports. However, the works presented in the literature have been limited to wireless cable method for 2×2 MIMO terminals so far, to the best knowledge of the authors.

To further improve UE antenna performance, the number of UE antennas on the terminals is expected to increase in the near future. For example, up to eight receive antennas have been introduced in LTE-Advanced (Release 10 and beyond) [1]. Wireless connectivity for automobiles, realized with LTE or dedicated short range communication systems, is vital in the foreseeable future. Multi-antenna technique on automobiles is seen as enabling technology to offer high data rate and reliable communications (in both line of sight (LOS) and non-LOS scenarios) in the next generation advanced driver

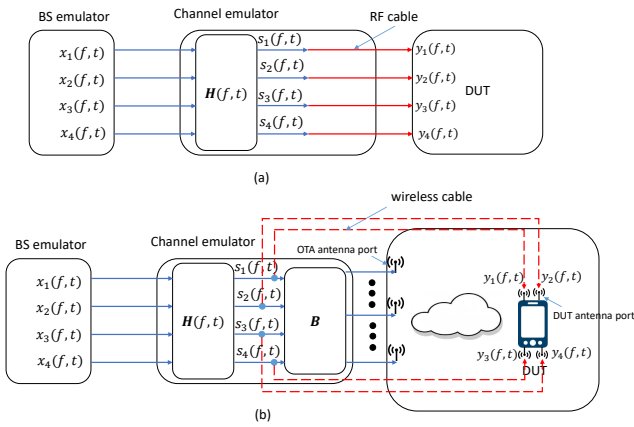


Figure 1. Block diagram of the conducted cable setup (a) and the wireless cable setup (b). 4×4 MIMO is set as an example in the diagram.

assist systems [4], [16]–[21]. Unlike mobile terminals, the number of antennas in automotive applications can be large, due to the large form factor. The wireless cable method can be readily applied to evaluate the performances of high-order antenna systems in principle. However, a cost-efficient wireless cable method for high-order MIMO systems has not been reported so far. In [4], a brute-force method was proposed to determine the calibration matrix and the calibration matrix was implemented via allocating complex weights to the CE output ports. For high-order MIMO systems, the technique proposed in [4] is not directly applicable, due to high computation time to determine the calibration matrix and high system cost to implement the calibration matrix. There is a strong need for a computationally efficient method to determine the calibration matrix and a cheap way to implement the calibration matrix in the CE. The main contributions of this paper are summarized as below:

- A general framework to establish wireless cable connections for a $M \times N$ MIMO system with K OTA antennas is presented.
- An efficient PSO algorithm is proposed to determine the calibration matrix for high-order MIMO terminals.
- A novel implementation of the wireless cable method in the CE is proposed. The number of required CE output ports can be reduced from N^2 to N with the proposed implementation scheme.
- Validation measurements in an anechoic chamber are provided to demonstrate the effectiveness of the proposed PSO algorithm for two 4×4 practical MIMO mockups.

II. PROBLEM FORMULATION

The wideband MIMO signal model can be expressed as:

$$\mathbf{y}(f, t) = \mathbf{H}(f, t)\mathbf{x}(f, t) + \mathbf{n}(f, t) = \mathbf{s}(f, t) + \mathbf{n}(f, t), \quad (1)$$

where $\mathbf{y}(f, t) \in \mathbb{C}^{N \times 1}$ denotes the receive signal vector at the N UE antenna ports, $\mathbf{s}(f, t) \in \mathbb{C}^{N \times 1}$ the specified testing signal vector at the N UE antenna ports, $\mathbf{x}(f, t) \in \mathbb{C}^{M \times 1}$ the transmit signal vector at the M base station (BS) antenna ports, $\mathbf{n}(f, t) \in \mathbb{C}^{N \times 1}$ the noise vector, and $\mathbf{H}(f, t) \in \mathbb{C}^{N \times M}$ the

frequency response of the time-variant radio channel between the UE and BS antenna ports [22], [23], respectively. The geometry based stochastic channel model (GBSC) enables separation of antennas and propagation channels and therefore are selected in standards for MIMO performance evaluation [22]. Without loss of generality, we assume $M \geq N$ in the paper. In typical UE testing setup, a base station (BS) emulator is used to emulate the BS end of the link, and a radio CE is used to emulate the radio channel between the BS antenna ports and UE antenna ports. To ensure the desired test signal $s_n(f, t)$ is received at n^{th} DUT antenna port for $n \in [1, N]$ undistorted, there are several alternatives:

a) *Conducted cable setup*: With the conducted cable setup, desired signals can be directly guided to the intended antenna ports by RF cables, with no cross-talks to other antenna ports in the ideal case, as shown in Fig. 1 (a). As explained earlier, though simple and attractive for device testing in the early stage, conducted testing presents many shortcomings and hence there is a strong need to avoid actual RF cable connections in the conducted cable setup.

b) *Antenna coupler connection setup*: The basic idea is that antenna couplers can be utilized to couple the test signals to desired built-in DUT antennas. In the ideal scenario, the coupling loss between the antenna coupler and the desired built-in antenna is low, while the isolations between the antenna coupler and undesired built-in antennas (i.e. cross-talk links) are high. The antenna coupler solution has been used for single antenna mobile terminals to avoid complicated wiring and handling in the industry [24], where a moving shuttle is typically utilized to ensure that the best coupling position can be found for the antenna coupler. However, it will become more difficult when the antenna count on the mobile terminal gets larger and antenna spacing gets smaller. Antenna coupling solutions for multi-antenna terminals are yet to be implemented, to the best knowledge of authors.

c) *Wireless cable connection setup*: The wireless cable method is essentially an RF cable replacement technique, where we can achieve cable connection functionality, without actual RF cable connections, as shown in Fig. 1 (b). Assuming the transfer matrix between the OTA antenna ports and DUT antenna ports is $\mathbf{A} \in \mathbb{C}^{N \times K}$, we have,

$$\begin{aligned} \mathbf{y}(f, t) &= \mathbf{A}\mathbf{H}_{CE}(f, t)\mathbf{x}(f, t) + \mathbf{n}(f, t) \\ &= \mathbf{A}\mathbf{B}\mathbf{s}(f, t) + \mathbf{n}(f, t), \end{aligned} \quad (2)$$

where $\mathbf{H}_{CE}(f, t) = \mathbf{B}\mathbf{H}(f, t)$ is the channel models implemented in the CE. To achieve wireless cable connection, we need to set calibration matrix $\mathbf{B} \in \mathbb{C}^{K \times N}$ in the CE so that $\mathbf{A}\mathbf{B} = \mathbf{I}_N$ can be approximated. Once we have the knowledge of the \mathbf{A} , we can obtain the \mathbf{B} via performing Moore-Penrose pseudo inverse of \mathbf{A} or utilizing precoding methods, such as zero forcing or minimum mean square error (MMSE) algorithms to achieve wireless cable functionality. There are several possibilities to determine \mathbf{A} :

- 1) One straightforward idea is to directly estimate \mathbf{A} . To determine \mathbf{A} , we need to set channel models in a bypass mode in the CE (i.e. $\mathbf{H}_{CE}(f, t) = \mathbf{I}_N$) to achieve

$\mathbf{y}(f, t) = \mathbf{A}\mathbf{x}(f, t)$. A popular approach in channel estimation is to utilize pilot sequence. A known pilot signal $\hat{\mathbf{x}}(f, t)$ can be transmitted from the BS emulator and the channel matrix \mathbf{A} is estimated using the combined knowledge of the transmitted signal $\hat{\mathbf{x}}(f, t)$ and received signal $\hat{\mathbf{y}}(f, t)$. The LTE receiver has the knowledge of the channel matrix to decode the transmitted signals. However, the channel matrix \mathbf{A} is not stored in the UE, and can not be reported. Therefore, the channel matrix is not accessible for testing purposes.

- 2) As proposed in the radiated two stage (RTS) method for 2×2 MIMO systems [3], [13], \mathbf{A} can be calculated from the measured complex OTA antenna patterns, the LOS propagation coefficients from OTA antennas to DUT antennas, and the complex DUT antenna patterns. However, a non-intrusive DUT antenna pattern measurement is currently not mandatory in any standard and thus not enabled by all terminal vendors. Furthermore, it requires a large anechoic chamber to ensure ideal LOS propagation. Furthermore, the applicability of the method for high-order MIMO has not been demonstrated yet.
- 3) In [4], a technique to determine the calibration matrix \mathbf{B} via monitoring the reference signal received power (RSRP) per DUT antenna port was presented. With an LTE connection established between the UE and the BS, the RSRP value per UE antenna port can be recorded and collected via commercially available software toolsets installed in the computer via universal serial bus (USB) connection, i.e. without a need to open the UE terminal case. The calibration matrix is implemented via selecting optimal complex weights in the CE output ports [4]. The method can be executed in a small RF shielded box to significantly reduce setup cost. Furthermore, the method works for any LTE terminal, without the need for special chipset support. The method in [4] works for 2×2 MIMO systems. However, its computation complexity and system cost scale up rapidly with the increase of DUT antenna count. First, for $M \times N$ MIMO systems, we need to determine minimal $(N - 1) \times N$ complex weights for N wireless cable connections and a total of minimal N^2 CE output ports are needed to implement the calibration matrix [4], as discussed later. Furthermore, the optimal complex weights are determined via an exhaustive search method [4]. For high-order MIMO systems, the brute-force method becomes computationally prohibitive and the system cost becomes high due to the large number of required CE output ports. There is a strong need for a computationally efficient method to determine the calibration matrix \mathbf{B} and a cheap way to implement the calibration matrix \mathbf{B} in the CE.

III. CALIBRATION MATRIX DETERMINATION AND IMPLEMENTATION FOR HIGH-ORDER MIMO TERMINALS

In this part, a general framework to achieve wireless cable connections for an $M \times N$ MIMO system with K OTA antennas is firstly derived. After that, a novel implementation of calibration matrix \mathbf{B} in the CE is proposed.

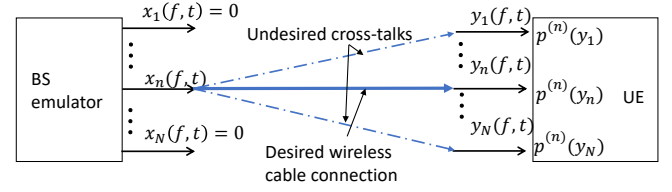


Figure 2. An illustration of the n^{th} wireless cable connection.

A. Calibration procedure

With K OTA antenna ports and N UE antenna ports, we need to establish N wireless cable connections, each associated with one UE antenna port. As explained, the goal is to determine calibration matrix \mathbf{B} such that $\mathbf{A}\mathbf{B}$ can approximate an identity matrix \mathbf{I}_N . To simplify the determination of the calibration matrix \mathbf{B} , firstly we need to remove the effect of radio channel models in the CE. We can bypass channel model at the calibration stage by substituting $\mathbf{H}_{CE}(f, t)$ as:

$$\mathbf{H}_{CE}(f, t) = \mathbf{B}\mathbf{H}(f, t) = \mathbf{B} \begin{bmatrix} \mathbf{I}_N & \mathbf{0}_{N \times (M-N)} \end{bmatrix}, \quad (3)$$

where $\mathbf{0}_{N \times (M-N)} \in \mathbb{R}^{N \times (M-N)}$ is a matrix with all zero entries. Ignoring the noise term, the signal model can be rewritten as:

$$\mathbf{y}(f, t) = \mathbf{A}\mathbf{H}_{CE}(f, t)\mathbf{x}(f, t) = \mathbf{A}\mathbf{B}\hat{\mathbf{x}}(f, t), \quad (4)$$

where $\hat{\mathbf{x}}(f, t) = [x_1(f, t), \dots, x_N(f, t)]^T$ is the known transmit signal vector and the average power of transmit signal x_n for $n \in [1, N]$ is set to P . Applying (3), we have a $N \times N$ MIMO system, as denoted in (4).

In the calibration procedure, we first need to determine the calibration matrix for each wireless cable connection, i.e. $\mathbf{B}^{(n)}$ for the n^{th} wireless cable connection for $n \in [1, N]$. It is noted that superscript n denotes the n^{th} wireless cable in the paper. After that, the calibration matrix \mathbf{B} to achieve N wireless cable connections to the N UE antenna ports can be constructed from $\mathbf{B}^{(n)}$ ($n \in [1, N]$), as discussed later.

For the n^{th} wireless cable connection, we should disable the other $(N - 1)$ BS antennas, as illustrated in Fig. 2. To achieve this, The calibration matrix $\mathbf{B}^{(n)}$ can be set in a general way as:

$$\mathbf{B}^{(n)} = a^{(n)} \cdot \begin{bmatrix} \mathbf{0}_{K \times (n-1)} & \begin{pmatrix} w_{1n} \\ \vdots \\ w_{kn} \\ \vdots \\ w_{Kn} \end{pmatrix} & \mathbf{0}_{K \times (N-n)} \end{bmatrix}, \quad (5)$$

where $\{w_{kn}\}$ with $k \in [1, K]$ in the n^{th} column are the K complex weights to control the isolation between the n^{th} wireless cable connection and other $N - 1$ undesired cross-talks. The $(N - 1)$ columns with zero entries are set to disable the other $(N - 1)$ BS antennas. $a^{(n)}$ is a scaling value to control the signal level of the n^{th} wireless cable connection.

To achieve an ideal wireless cable connection, we need to ensure that each transmit signal can be directly guided to an

associated antenna port on the UE without distortion, with no cross-talks to the other UE antenna ports. From (4) and (5), we have

$$\mathbf{y}^{(n)}(f, t) = a^{(n)} \mathbf{A} \begin{bmatrix} w_{1n} \\ \vdots \\ w_{kn} \\ \vdots \\ w_{Kn} \end{bmatrix} x_n(f, t) = c \begin{bmatrix} 0 \\ \vdots \\ x_n(f, t) \\ \vdots \\ 0 \end{bmatrix}, \quad (6)$$

where $\mathbf{y}^{(n)}(f, t)$ denotes the received signal vector with the n^{th} BS antenna port active and c is a common loss factor for all N wireless cable connections. For the n^{th} wireless cable connection, the RSRP value $P^{(n)}(y_j)$ received by the j^{th} UE antenna port ($j \in [1, N]$) in an ideal case should satisfy:

$$P^{(n)}(y_j) = \begin{cases} 0 & j \neq n \\ |c|^2 \cdot P & j = n \end{cases}, \quad (7)$$

To achieve N ideal wireless cable connections, we need to ensure that no cross-talks for each wireless cable connection and balanced branches across N desired wireless cable connections. In a practical setup, this can be approximated in two steps:

- 1) Maximizing isolation levels between the desired direct link and undesired cross-talks for each wireless cable connection, via selecting $\{w_{kn}\}$. Therefore, for the n^{th} wireless cable connection, the objective function can be written as:

$$\max_{w_{kn}, k \in [1, K]} \left\{ \frac{P^{(n)}(y_j), j = n}{\max \{P^{(n)}(y_j), j \neq n\}} \right\}. \quad (8)$$

Basically, we optimize K complex weights to maximize the isolation level between the desired link and cross-links. The quality of the n^{th} wireless cable connection is determined by the isolation level between the desired link and the worst cross link (i.e. with maximum power level). Generally speaking, we have K complex weights to be determined (i.e. search space of dimension K) for each wireless cable connection and we have N wireless cable connections to be established in total.

- 2) Balancing the achieved N wireless cable connections, via selecting $a^{(n)}$. For the n^{th} wireless cable connection, once the complex weights $\{w_{kn}\}$ have been determined and set for $k \in [1, K]$, the isolation levels between the crosstalk links and desired link are fixed. Balanced branches can be achieved via adjusting $a^{(n)}$ for $n \in [1, N]$, according to Eq. (7) as:

$$P^{(1)}(y_1) = \dots P^{(n)}(y_n) = \dots P^{(N)}(y_N). \quad (9)$$

Equation (4) can be seen as a linear time-invariant system where $\mathbf{y}(f, t)$ is the response of a linear and time-invariant system to an arbitrary input signal \mathbf{B} . According to the linearity properties of a linear time-invariant system, the calibration matrix for N wireless cable connections can be constructed as:

$$\mathbf{B} = \sum_{n=1}^N \mathbf{B}^{(n)}, \quad (10)$$

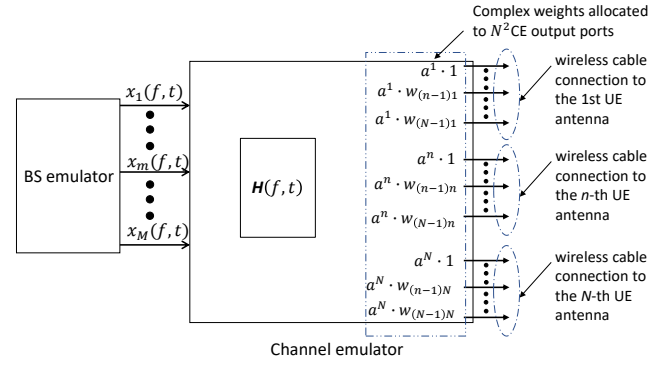


Figure 3. An illustration of calibration matrix implementation via allocating complex weights to CE output ports.

whose element can be expressed as $\mathbf{B} = \{b_{kn}\} \in \mathbb{C}^{K \times N}$ with $b_{kn} = a^{(n)} \cdot w_{kn}$.

It is noted that we need to ensure the number of OTA antennas (K) is no less than the number of UE antenna ports (N) in the system design. \mathbf{AB} would fail to approximate \mathbf{I}_N with $K < N$, since it would be rank deficient:

$$\text{rank}(\mathbf{AB}) \leq \min(\text{rank}(\mathbf{A}), \text{rank}(\mathbf{B})) \leq K < N, \quad (11)$$

where $\text{rank}()$ denotes the rank operator.

After the calibration procedure, $\mathbf{AB} = \mathbf{I}_N$ can be approximated and N wireless cable connections to N UE antenna ports can be established. MIMO performance testing with various channel models $\mathbf{H}(f, t)$ can be performed, as in the conducted cable testing.

B. Calibration matrix implementation

In Section III-A, a general procedure to determine the calibration matrix for a $M \times N$ MIMO system with K OTA antennas is detailed. In this part, we discuss how to implement the calibration matrix in the CE.

One straightforward way to implement the calibration matrix is to allocate complex weights to the CE output ports in the RF band, as shown in Fig. 3. Basically, $\mathbf{B}^{(n)}$ can be achieved via enabling N CE output ports associated to the n^{th} wireless cable connection and disabling all the other $(N-1) \times N$ CE output ports. Once $\mathbf{B}^{(n)}$ is determined for $n \in [1, N]$, \mathbf{B} can be realized via enabling all N^2 CE output ports. Adopting this implementation scheme, we need N^2 CE output ports to implement the calibration matrix for a UE system with N antennas. For example, 4 CE output ports are needed in the implementation for a 2×2 MIMO system in [4]. This is problematic for high-order MIMO systems, since the system setup cost would increase significantly as N gets large.

In the paper, we propose to directly implement the calibration matrix in the digital baseband of the CE. The channel model to be implemented in the CE between the m^{th} BS antenna port and the k^{th} CE output port is:

$$h_{km}^{CE}(f, t) = \sum_{n=1}^N b_{kn} \cdot h_{nm}(f, t) \quad (12)$$

It requires two operations on the desired channel model $h_{nm}(f, t)$ with $n \in [1, N]$ and $m \in [1, M]$, i.e. multiplication with a complex value and summation. These two operations can be easily realized with a digital CE in the baseband. This way, the calibration matrix \mathbf{B} can be implemented with only $K = N$ CE output ports. The proposed implementation structure can significantly reduce the system cost and therefore suitable for high-order MIMO terminals.

IV. PSO ALGORITHM AND SIMULATION RESULTS

As discussed in Section III-A, we need to determine K complex weights $\{w_{kn}\}$ to achieve the n^{th} wireless cable connection in a general form. To achieve N wireless cable connections, a total of $K \times N$ complex weights are to be determined. The brute-force method proposed in [4] for 2×2 MIMO systems would become computationally prohibitive. To speed up in the calibration procedure, we need an efficient algorithm to determine complex weights. The main contribution of this part is that a simple yet efficient PSO algorithm is proposed to determine complex weights.

A. Introduction

The PSO is a numerical optimization technique, inspired by the social swarm behavior [25]. The PSO has found wide applications in electromagnetic optimization problems due to its capability to solve problems many orders of magnitude faster than exhaustive brute-force searches. The PSO has proven to be an effective optimization technique for multi-dimensional optimization problem. A limitation is that it cannot guarantee a global optimal solution to be found, though highly likely to. However, compared to the popular and widely successful genetic algorithm (GA), the PSO is more attractive due to its simplicity and capability to control convergence [25], [26]. The GA is implemented as a reference random search method [27] in the paper. The implementation of the GA follows [27] and not detailed.

The fitness function can be measured by the isolation levels between the desired link and cross-talk links. In this section, a PSO applied to determine complex weights is described. The concept is straightforward: The PSO seeks for a set of complex weights that would maximize the isolation levels for each wireless cable connection.

B. PSO implementation

A flowchart of the PSO and the PSO procedure are detailed in [25] and only outlined here:

- 1) Define the solution space. A swarm is a collection of particles, and each particle contains K complex variables which represent the K complex weights. The purpose of the optimization is to find complex values for the K parameters that define the quality of a wireless cable. Therefore, these parameters define a K dimensional solution space where the PSO searches for the optimal wireless cable connection. For each parameter, a phase term within $[-\pi, \pi]$ and an amplitude term within $[0, a_{\max}]$ are defined, where a_{\max} denotes the maximum value for the amplitude term.

- 2) Define a fitness function. The fitness function is defined by the quality of the wireless cable, i.e. isolation level between the desired direct link and undesired cross-talks for each wireless cable connection. In practice, the isolation level is calculated based on the measured average power per UE antenna port. For the n^{th} wireless cable connection, the evaluation function is defined as:

$$\Phi_n = \frac{P^{(n)}(y_n | w_{kn}, k \in [1, K])}{\max \{P^{(n)}(y_j), j \neq n | w_{kn}, k \in [1, K]\}}. \quad (13)$$

- 3) Define optimization parameter settings. For our study, a population of 30 was selected for the swarm, correction factors c_1 and c_2 were both set to 2, the inertial weight was set to 1 and a_{\max} was set to 1 for the PSO algorithm [25].
- 4) Define the stop criteria. To constrain the computation complexity, a stop criteria needs to be defined. In the PSO implementation, we can define either the maximum number of iterations N_i or the desired isolation threshold levels. Therefore, the complexity of PSO to achieve N wireless cable connections is upbounded by $N_{\text{pop}} \times N_i \times N$, with N_{pop} the population size of the swarm.
- 5) Run the PSO algorithms to determine the K complex weights for each wireless cable connection $\{w_{kn}\}$ with $n \in [1, N]$.
- 6) Determine $a^{(n)}$ for $n \in [1, N]$ according to (9).

After step 1 to 6, the calibration matrix $\mathbf{B} = \{a^{(n)} \cdot w_{kn}\} \in \mathbb{C}^{K \times N}$ can be determined.

C. Simulation results

To demonstrate the robustness of the proposed PSO algorithm, 60 transfer matrices \mathbf{A} are randomly generated, where each transfer matrix \mathbf{A} is realized as

$$\mathbf{A} = [0.1 + 0.9 * \text{rand}(4, 4)] \circ \exp(j2\pi * \text{rand}(4, 4)), \quad (14)$$

where $\text{rand}(q, p)$ returns a $q \times p$ real matrix with each entry randomly drawn from the uniform distribution within $[0, 1]$. Therefore, the amplitude and phase range of the $(n, k)^{\text{th}}$ entry $a_{n,k}$ are $[0.1, 1]$ and $[0, 2\pi]$, respectively. \circ denotes entry-wise product. For each randomly generated transfer matrix \mathbf{A} , 100 runs with a random initial weight each time are performed by using the PSO algorithm and the GA, respectively. It is noted that, both the PSO algorithm and the continuous GA have a population size of 30 and the maximum iterations number of 100. That is, the number of function evaluations is 30×100 for both algorithms for a fair comparison. For the GA, a mutation rate 0.15 and a selection rate 0.5 are selected. Fig. 4 displays the isolation level achieved by the PSO algorithm and the GA. The results are averaged over 100 runs for both algorithms. It shows that the PSO algorithm significantly outperforms the GA with the same number of function evaluations. Based on the simulation results, the PSO algorithm is selected as the random search method to determine the calibration matrix \mathbf{B} .

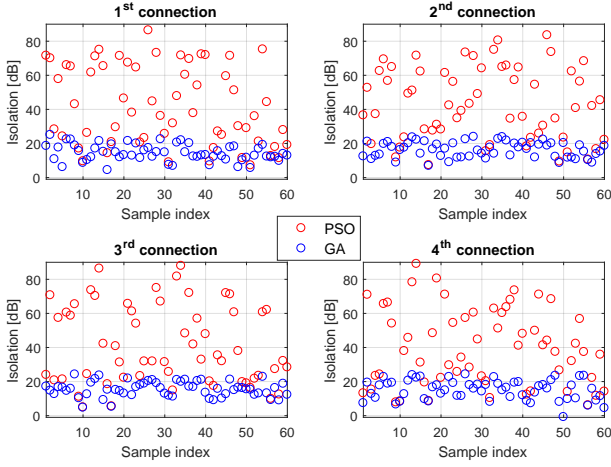


Figure 4. Achieved average isolation per wireless connection over 100 runs for the 4×4 MIMO system with the PSO and GA algorithm.

V. MEASUREMENT VALIDATION

In [3], [4], active throughput measurements were reported for 2×2 MIMO systems with the LTE downlink open-loop spatial multiplexing transmission mode to validate the wireless cable method. To validate the wireless cable method for high-order MIMO systems in active throughput measurements, we need a BS emulator to support high-order MIMO transmission, a high-order MIMO LTE handset, and a software tool to record RSRP value per DUT antenna port. Throughput measurements for high-order MIMO systems (i.e. > 2) are currently not feasible due to lack of measurement facilities, though the situation might change in the near future. As an alternative method to validate the proposed algorithm, we can directly measure the transfer matrix \mathbf{A} in realistic setups and investigate how fast and how well the calibration matrix \mathbf{B} can be determined with the proposed PSO algorithm. It is noted that this is only feasible for mock-up antennas with accessible antenna connectors, not for commercial UEs. As explained earlier, with the RTS method, the measured transfer matrix \mathbf{A} can be directly inverted to obtain the calibration matrix \mathbf{B} . In this work, we determine the calibration matrix \mathbf{B} based on the average received power value per mock-up antenna port.

A. Measurement system

As illustrated in Fig. 5, the measurement system consists of a five-port vector network analyzer (VNA), four OTA antennas, a single pole quad throw switch and two different mock-ups, each equipped with four antennas. As explained, to achieve wireless cable connection, we need to set the calibration matrix \mathbf{B} in the CE. In principle, \mathbf{B} exists if \mathbf{A} is not rank deficient. However, in practice, we might need to sweep a large dynamic range to obtain the optimal amplitude term, which might be not supported due to the limited dynamic range of the CE. Furthermore, it might take a long calibration time to sweep a large amplitude range. The transfer matrix \mathbf{A} includes the effects of OTA antennas, multipath propagation inside the small RF shielded enclosure,

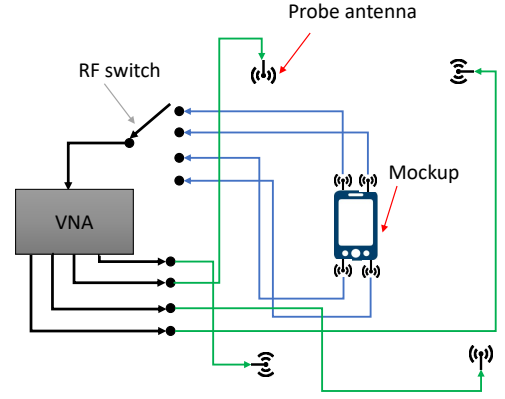


Figure 5. An illustration of the measurement system.

DUT antennas, RF cables and connectors. As the RF shielded enclosure might be small, strong reflections might exist besides the LOS connection. Furthermore, the DUT antennas might not be placed in the far field of the OTA antennas due to the small distance. As a summary, \mathbf{A} matrix will be highly sensitive to the DUT orientation, DUT location, OTA antenna placement and the RF shielded enclosure. Therefore, it is difficult to determine the optimal OTA antenna placement, unlike pure the LOS transmission scenario [28]. OTA antennas are separated to increase the odds of reaching full rank \mathbf{A} in the measurement setup. In unfortunate cases where \mathbf{A} is found to be rank deficient, either OTA antennas or the DUT must be moved to get favorable conditions for establishing the wireless cables.

The measurement setup is detailed in Table I. Basically, the transfer matrix \mathbf{A} can be measured, via recording the frequency responses of 16 transmission coefficients (i.e. from four OTA antennas to four antennas on the mock-up, respectively) with the VNA, with the help of the RF switch. As explained in Section III, the transfer matrix \mathbf{A} should be maintained static and unaltered during the whole measurement. Therefore, we need an RF enclosure, which can shield external unwanted interference. The measurement was therefore performed in an anechoic chamber, and the VNA together with the switch control were placed in another control room outside of the anechoic chamber. Note that a small RF shielded anechoic enclosure will be most likely used as the test environment in practice for cost consideration [4]. It is noted that the investigation is limited to the mockup frequency, though the principle can be directly applied for current LTE frequencies. The measured channel frequency response and channel impulse response between a OTA antenna port and a DUT antenna port is shown in Fig. 8 as an example.

B. PSO parameter settings

The PSO was applied to a subset of the measured data from 5.7147 to 5.7347GHz with a total of 65 frequency samples as an example. The bandwidth of the selected subband is 20 MHz, which is comparable to LTE bandwidth. The population size for each swarm is set to $N_{Pop} = 30$, and maximum

Table I
SETUP AND SPECIFICATIONS OF EACH COMPONENT IN THE MEASUREMENT SYSTEM

Component	Setup and specifications
VNA	The frequency sweep was recorded from 5.1 GHz to 5.8 GHz with 2241 frequency samples. Intermediate frequency (IF) in the VNA was set to 1 KHz. It is noted that the 5-port VNA was realized via direct access to the receiver port, by disconnecting front panel jumpers (standard option 401 in Keysight N5227A VNA).
OTA antenna	Linear polarized directional antennas with frequency band from 5.15 GHz to 5.875 GHz and the product type is SPA-5600/40/14/0/V. The OTA antennas are placed on the four vertices of a square, each side around 1 m, as shown in Fig. 6.
Mock-up	Two different mock-ups with four wideband monopole antenna elements were designed, as shown in Fig. 7. The two mock-ups operate at around 5.5 GHz. The mock-ups were placed on a polystyrene support with approximately 45° tilted, approximately same height as the OTA antennas.

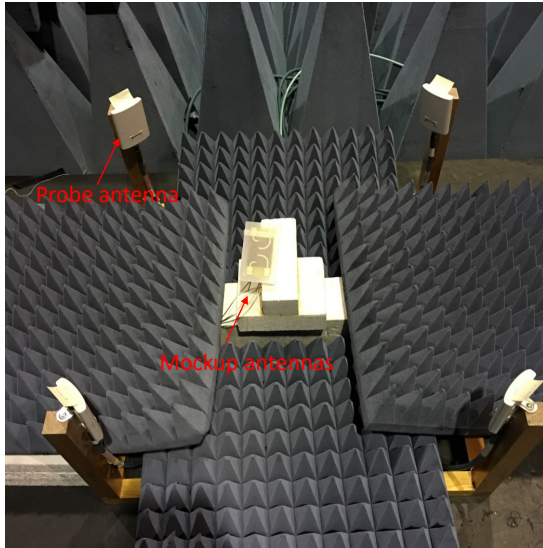


Figure 6. A photo of the measurement setup in the anechoic chamber.

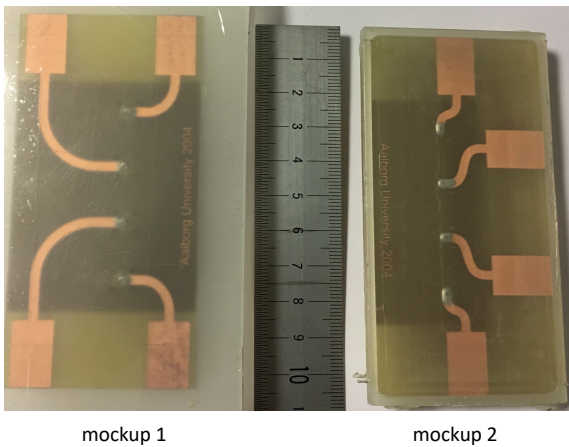


Figure 7. Two mock-ups in the measurement campaign

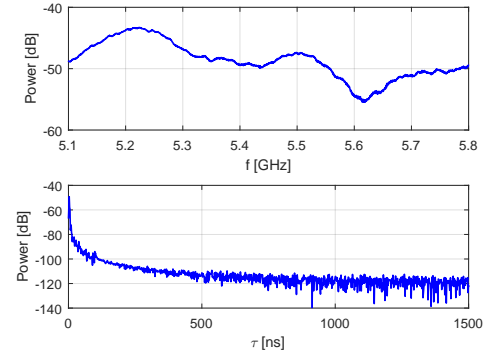


Figure 8. The measured channel frequency response (top) and channel impulse response (below) between OTA antenna 1 and DUT antenna 1 for the mockup 2.

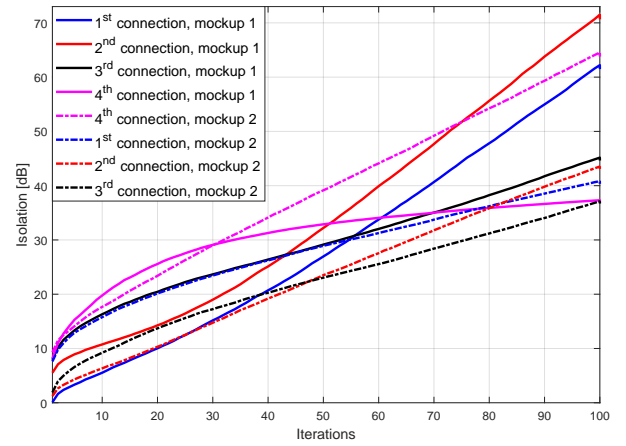


Figure 9. Achieved average isolation per wireless cable for mockup 1 (solid line) and mockup 2 (dash line).

iterations are set to $N_i = 100$. We have $N = 4$ since each mockup is equipped with 4 antennas. In [4], it was mentioned that it took around 3 minutes to sweep around 400 complex weights for the 2×2 MIMO terminal. With the parameter setting for the PSO algorithm, it would take around 90 minutes to establish the wireless cable connection in the worst scenario for the 4×4 MIMO mockup (i.e. 100 iterations).

C. Measurement results

The initial variables are generated randomly in the PSO for the center frequency sample (i.e. at 5.7247 GHz) and 100 runs are performed to demonstrate the robustness of the PSO algorithm. Fig. 9 displays the average isolation levels achieved by the PSO algorithm over 100 runs. The curves show that average isolation value returned versus the number of calls to the fitness function evaluator. The PSO is attempting to reach the high isolation value for each iteration. A minimum isolation of 35 dB can be achieved for the worst scenario over 100 iterations. The convergence curves for the mockup 1 and mockup 2 at $f_c = 5.7247$ GHz indicate the effectiveness and robustness of the PSO.

The measured throughput results demonstrated that an isolation level of 11 dB is sufficient to establish a good

$$A = \begin{pmatrix} 0.0181 - 0.0248i & -0.0020 - 0.0199i & 0.0023 - 0.0088i & 0.0450 - 0.0304i \\ 0.0264 - 0.0085i & -0.0385 + 0.0107i & 0.0043 + 0.0175i & 0.0646 + 0.0231i \\ 0.0115 - 0.0160i & -0.0278 + 0.0009i & -0.0387 - 0.0453i & -0.0241 + 0.0093i \\ -0.0006 + 0.0337i & -0.0006 + 0.0337i & 0.0277 + 0.0372i & -0.0132 - 0.0526i \end{pmatrix}$$

$$a^{(1)} \begin{pmatrix} \omega_{11} \\ \omega_{21} \\ \omega_{31} \\ \omega_{41} \end{pmatrix} = 36.86 \cdot \begin{pmatrix} 0.177 + 0.711i \\ 0.092 + 0.471i \\ 0.031 - 0.281i \\ -0.073 + 0.039i \end{pmatrix}$$

$$a^{(2)} \begin{pmatrix} \omega_{12} \\ \omega_{22} \\ \omega_{32} \\ \omega_{42} \end{pmatrix} = 22.46 \cdot \begin{pmatrix} -0.284 - 0.168i \\ -0.722 + 0.102i \\ 0.216 - 0.018i \\ 0.288 - 0.179i \end{pmatrix}$$

$$a^{(3)} \begin{pmatrix} \omega_{13} \\ \omega_{23} \\ \omega_{33} \\ \omega_{43} \end{pmatrix} = 28.23 \cdot \begin{pmatrix} 0.479 - 0.429i \\ -0.105 - 0.252i \\ -0.660 + 0.167i \\ -0.040 + 0.265i \end{pmatrix}$$

$$a^{(4)} \begin{pmatrix} \omega_{14} \\ \omega_{24} \\ \omega_{34} \\ \omega_{44} \end{pmatrix} = 46.52 \cdot \begin{pmatrix} -0.323 - 0.275i \\ -0.046 + 0.062i \\ -0.109 + 0.155i \\ 0.210 + 0.054i \end{pmatrix}$$

$$20 \lg(abs(A \times B)) = \begin{pmatrix} 0.0 & -26.5 & -23.6 & -23.3 \\ -24.5 & 0.0 & -25.3 & -29.9 \\ -22.2 & -23.3 & 0.0 & -24.9 \\ -30.3 & -30.6 & -21.3 & 0.0 \end{pmatrix}$$

Figure 10. The measured transfer matrix A and the determined calibration matrix B with the PSO at frequency $f_o = 5.7247$ GHz.

wireless cable connections for 2×2 MIMO systems [4]. In [29], measured throughput results demonstrated that with an isolation level around 15 dB, an RSRP error of around 0.5 dB at 70% maximum throughput can be observed. In practice, the target isolation level should increase as N grows, since unwanted cross talks might accumulate from the other $N - 1$ wireless cables. This aspect will be investigated in the future work, once the throughput measurements with high-order MIMO terminals become feasible. In this paper, the isolation threshold to stop the PSO is set to 20 dB in the following results, to leave some margin.

The measured transfer matrix A and the determined calibration matrix B with the PSO at frequency $f_c = 5.7247$ GHz for mockup 1 are shown in Fig. 10 as an example. As we can see, if uncompensated, the cross-talks (i.e. off-diagonal elements) can be stronger than desired connections (i.e. diagonal elements) in A . With the calibration matrix B , an isolation level of 22.7 dB, 22.3 dB, 22.4 dB and 21.9 dB can be achieved for the four wireless cable connections, respectively. The complex weights and scaling value for each wireless cable are shown in Fig. 10 for the 4×4 MIMO mockup.

As explained in [4], the basic idea of the wireless cable method is that we determine the calibration matrix B via monitoring the received RSRP value per DUT antenna. However, we only have one measured RSRP value available for each DUT antenna for the whole LTE band. Therefore, we need to check whether the calibration matrix B determined at center frequency f_c offers good isolation level for the whole frequency band B_f . The isolation levels which can be calculated as $A(f)B(f_c)$ with $f \in [f_c - \frac{B_f}{2}, f_c + \frac{B_f}{2}]$, is shown in Fig. 11 for mockup 1 as an example. As can be seen, though isolation level within the wireless cables decrease as frequency moves away from the center frequency, the performance deterioration is negligible. The measurement results have shown that the proposed PSO algorithm is efficient

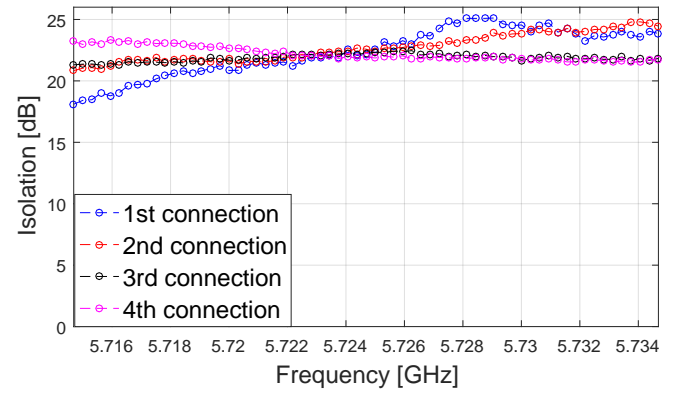


Figure 11. Isolation levels for mockup 1 with $B(f_c)$ across the frequency range of interest.

and simple to determine the calibration matrix.

VI. DISCUSSION

In this paper, 4×4 MIMO systems are selected to demonstrate the proposed PSO algorithm in the simulation and measurement results. The proposed PSO algorithm can be directly applied for MIMO systems with any antenna count in principle. In fact, the higher the DUT antenna count is, the more computationally-efficient the proposed PSO algorithm will be to achieve the wireless cable connection, compared to the brute-force algorithm. However, there are some practical limitations. With the wireless cable method, the number of required OTA antennas must be no less than the number of DUT antenna ports in principle to ensure full rank of transfer matrix A , as discussed. The next-generation antenna system will be more complicated, where utilization of millimeter wave (mmWave) frequencies and massive MIMO antenna arrays is expected. The antenna count might be massive (from tens to hundreds) and the antennas will be highly integrated. The use of wireless cable method for large-scale antenna systems is not practical, since the high number of required OTA antennas would result in costly and complicated testing setups. Furthermore, we have to calibrate out the transfer matrix A , which implies that the DUT antenna patterns must be static and not adaptive. The DUTs targeted in the paper are non-adaptive high-order LTE terminals and LTE-V systems, where the number of receive antennas is typically limited in the spatial transmission mode. It is noted that for end-to-end performance testing of large-scale adaptive antenna systems, the simple-sector MPAC (SS-MPAC) setup is actively discussed in the literature [30]–[32].

The transfer matrix A , which contains the DUT antenna characteristics, is calibrated out in the calibration stage. Therefore, the DUT antenna characteristics are not considered in the testing by default. DUT antennas are only utilized to provide the connectivity and the access to DUT. DUT antenna patterns, if known or measured, can be embedded with the propagation channel models in the CE. Therefore, DUT antenna characteristics can be indirectly considered. As a matter of fact, the RTS method proposed in [3], [13], [29] requires non-intrusive DUT antenna pattern measurement in the first stage

for MIMO OTA testing. It has been demonstrated that RTS method can effectively evaluate MIMO antenna performance. Nevertheless, the wireless cable method is a strong candidate in the standardization for 5G new radio (NR) demodulation testing [33]–[35]. The objective of demodulation testing is to evaluate the DUT's capability to demodulate test signals received at the antenna ports. As discussed, the wireless cable method is applicable if the DUT antenna pattern is not adaptive and number of antenna ports is limited. For mmWave DUTs equipped with hybrid or full analog beamforming structure, each antenna port will be equipped with an antenna array. The complex weight per array antenna element can be fixed to ensure the antenna pattern per DUT antenna port is static (i.e., beam-lock mode) [33]–[35]. The number of required OTA antennas only needs to match the number of antenna ports, which can greatly reduce the setup cost for the wireless cable method. In the beam-locked mode, we can utilize the wireless cable method to ensure desired test signals received at the DUT antenna ports. Therefore, it is believed that wireless cable method is valuable for future mmWave devices as well.

VII. CONCLUSION

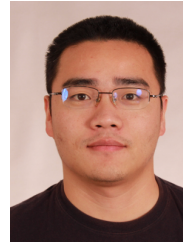
This paper discusses a wireless cable technique for a general $M \times N$ MIMO systems with K OTA antennas in the RF shielded enclosure. Based on the recorded RSRP value per UE antenna port, the calibration matrix to achieve N wireless cable connections can be determined based on the PSO algorithm. A novel way to implement the determined calibration matrix in the CE, which can significantly reduce the system cost, is proposed. With the proposed implementation scheme, the required number of CE output ports is N , compared to N^2 reported in the reference paper. Experimental validation results demonstrated the effectiveness of the proposed PSO. The measurement results showed that the proposed PSO algorithm is simple yet robust to determine the complex weights for achieving wireless cable connections. An minimum isolation level of 20 dB can be achieved with a population size of 30 in the swarm and a maximum iteration of 100 in the PSO for both 4×4 MIMO mockups.

There are some logical extensions for the presented work. For example, active throughput measurements of high-order MIMO terminals with the proposed algorithm are highly interesting and should be investigated, once the measurement system becomes available. The isolation threshold required to achieve good isolation should be determined for high order MIMO systems. The impact of hardware impairment on calibration matrix implementation in the CE should be investigated as well.

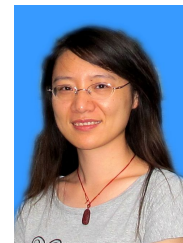
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enrolled. His research has focused on radio communication for mobile terminals especially small Antennas, Diversity systems, Propagation and Biological effects and he has published more than 175 peer reviewed papers and holds 28 patents. He has also worked as consultant for developments of more than 100 antennas for mobile terminals including the first internal antenna for mobile phones in 1994 with lowest SAR, first internal triple-band antenna in 1998 with low SAR and high TRP and TIS, and lately various multi antenna systems rated as the most efficient on the market. He has worked most of the time with joint university and industry projects and have received more than 12 M\$ in direct research funding. Latest he is the project leader of the SAFE project with a total budget of 8 M\$ investigating tunable front end including tunable antennas for the future multiband mobile phones. He has been one of the pioneers in establishing Over-The-Air (OTA) measurement systems. The measurement technique is now well established for mobile terminals with single antennas and he was chairing the various COST groups (swg2.2 of COST 259, 273, 2100 and now ICT1004) with liaison to 3GPP for over-the-air test of MIMO terminals. Presently he is deeply involved in MIMO OTA measurement.

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