A Coupled Random Search-Shape Grammar Algorithm for the Control of Reconfigurable Pixel Microstrip Antennas

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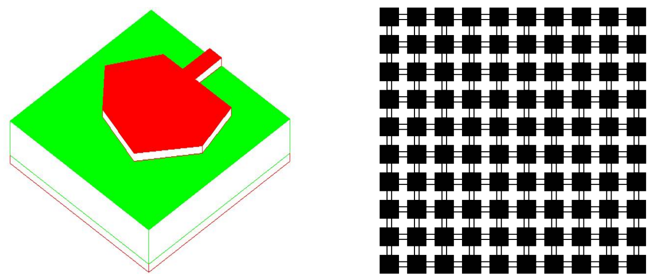
***Abstract*—Algorithms are necessary to reconfigure pixel antennas in real time. These algorithms must carry out an efficient search to yield the electrical specifications demanded by radio transceivers. To address this problem, an algorithm that combines a random search method with a shape grammar model is proposed. The performance of the algorithm is compared to a Genetic Algorithm with and without a pruning mechanism. Results demonstrate that the algorithm goes through a relatively very small number of iterations to converge to the antenna specifications and consequently outperforms the genetic-based searches.**

***Keywords*-Reconfigurable Pixel Antenna; Algorithm; Control; Shape Grammar**

I. Introduction

This paper deals with algorithms applied in the control of pixel microstrip antennas. The shape grammar based algorithm described in [1] is extended to a wider range of microstrip patch shapes and its performance is compared to a Genetic Algorithm (GA) and a GA augmented with a pruning mechanism.

The reconfigurable pixel microstrip antenna (RPMA) is a derivative of the microstrip antenna which consists of a radiating element backed by a ground plane. The radiating element is usually positioned 0.3 to $4mm$ above the ground plane and is physically supported either on a dielectric substrate or suspended under a superstrate. The radiating element can take the form of any useful shape and the final design of the antenna depends on the physical space that has been allocated to the antenna for the particular application as well as on the electrical characteristics specified. Fig.1(a) depicts a microstrip antenna with an arbitrarily shaped patch. To a certain extent, the antenna electrical properties depend on the shape of the radiating element. Subsequently, an antenna that is required to resonate at different frequencies requires the development of complex shapes that steer the current though the antenna in different paths for each resonant frequency. The design of such antennas is complex and requires many experimental iterations and modifications to produce the final prototype. An antenna that can alter its shape, and hence the electrical characteristics, in real-time under the control of an algorithm is therefore highly desirable. The delivery of such devices would mean that a single device re-configures itself to operate over a wide frequency range, optimizes the signal strength and/or changes polarization in a short period of time as demanded by the system [2].



(a) (b)

Figure 1. (a) Microstrip patch antenna structure with an arbitrary patch shape, and (b) Reconfigurable Pixel Microstrip Antenna (RPMA) that can change the radiator shape in real time.

Reconfigurable antennas can be classified either according to their physical composition or according to the fundamental parameters that can be modified and to what extent these parameters can be varied. Reconfigurable antennas are physically composed of switchable elements and tuning devices. Additionally, a control circuit and an algorithm is required to operate the switches. Simple re-configurable antennas contain very few switching devices to switch a parameter over a few discrete values and hence do not really need a complex smart control algorithm. On the other hand the pixel microstrip antenna is a much more complex antenna that can tune the parameters over a wide range and can for example switch to any arbitrary frequency or optimize the signal strength received or polarization diversity in real-time. This type of antenna can function as a “universal” antenna that can be applied to spectrum monitoring, in security situations to rapidly scan a wide bandwidth or in a cognitive radio. The major advantage over fixed wideband antennas is the ability to tune to particular narrow bands and/or change the direction of the main lobe. Fig.1(b) depicts the general pixel microstrip patch structure, consisting of an $n \times m$ array of pixels, interconnected with switches. The switches can then be turned ON or OFF to synthesize an arbitrary patch shape. Various shapes synthesized from a 10×10 pixel array are shown in Fig.2.

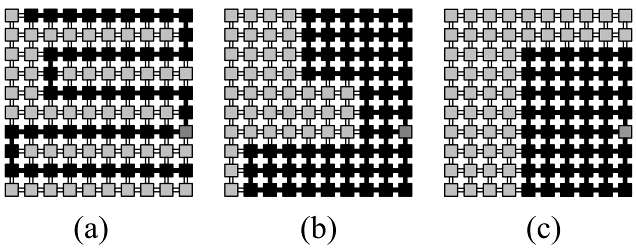


Figure 2. Antenna shapes synthesized with a RPMA (a) low, (b) medium, and (c) high frequency of operation.

The patch shapes synthesized by a RPMA are discrete and not continuous. This results in a structure whose frequency of resonance can be tuned in discrete steps and could lead to gaps along the frequency band. Various techniques have been proposed to mitigate these problems, for example the use of switchable shorting posts and the use of a tunable reactive component . However these add to complexity, have a negative effect on the antenna efficiency and limit the number of possible configurations [3]. Shorting posts are however useful in size reduction. On the other hand some degree of fine tuning can be obtained by taking advantage of the inherent reactive properties in the pixels and by suitably perturbing the shape a better match can be found. Furthermore it is usual and desirable to add a final matching stage to the antenna port [4]. A RPMA with a tunable matching circuit is described in [5]. It is also convenient and practical to have the probe feed at a fixed position. In this case the shape has to be rotated to suit the position of the feed. In summary, there are two aspects that the control algorithm has to address, (1) the minimization of switching, contributing to a longer lifetime, shorter convergence time and lower power consumption, and (2) making full use of reconfigurability to minimize the burden on the final tuning circuit.

A pixel reconfigurable antenna system therefore consists of the reconfigurable hardware parts and the control algorithm, on which the transient performance largely depends. Most of the research effort to-date has been targeted towards the hardware issues and the development of efficient control algorithms still needs to be adequately addressed.

In this section the reconfigurable pixel microstrip antenna is described and its inherent limitations and problems are discussed. Furthermore the tasks and targets for the control algorithm are defined. The rest of the paper is organized as follows. Section II describes related work and motivation. Section III reports a preliminary study that indicates the effectiveness of embedding domain knowledge in a search algorithm and discusses the importance of an algorithm that deals directly with shape. Section IV is a detailed description of the algorithm and discusses the results obtained. The last section outlines further work required to solve remaining issues.

II. Related Work

The research field in reconfigurable microstrip antennas is very active with several research groups seeking the best possible structure to dynamically modify the characteristics efficiently. The most salient design issues from the point of view of hardware include, distortion due to non-linear properties of devices, overall loss in structure and the overall lifetime of the devices. Due to their linear properties micro-electro-mechanical-switches (MEMS) are very suitable switching devices for this application and prototypes have been proposed and built [5], [6] using MEMS. Cetiner et al [5] designed an 8×8 pixel patch antenna whose resonant frequency could be tuned to two bands 4.1GHz and 6.1GHz and for each band the polarization could be changed to linear, right or left hand polarization. These operating modes were achieved by switching on or off different pixels in the antenna. The main application of this pixel patch antenna is in MIMO systems to enhance the overall operation. Grau et al [7] developed a software defined pixel antenna which could be tuned over a range of range 1GHz. The pixels were connected together using MEMS switches. The pixels are switched in such a way that a circular structure is created and the radius of the circular structure yields the operating frequency and polarization. A competing structure consisting of ceramic pistons that push in and out metallic pixels is reported in [8]. The latter structure avoids the use of switches.

In the RECAP project ([9], [10] and [11]) a fully reconfigurable monopole planar antenna that operates from 0.8GHz to 1.5GHz is developed. Pringle at al describe a pixel patch antenna, where each pixel in the antenna is electrically small (less than λ/50) and interconnected by an optically switched FET. The antenna is $22.5cm$ by $22.0cm$ and has a bandwidth of 800MHz. The antenna was designed with left-right symmetry and in total consists of 208 switches. A genetic algorithm together with a Finite-Difference-Time-Domain (FDTD) model were used to derive the operating frequency and radiation pattern off-line. Due to mismatches in the feed the antenna gain was smaller than simulated.

A Self Structuring Antenna (SSA) [12] is another type of reconfigurable wire antenna. Instead of having an array of switches to connect patches together, the SSA is made up of a number of wires or patches connected with a series of interconnections to increase the antenna's size. Using a microprocessor, a feedback system and a Genetic algorithm the SSA can be configured over a large bandwidth.

Most of the work carried out on the control algorithm considers the Genetic Algorithm (GA) in the optimization of signal strength and operation at different frequencies. In [13] and [14], the GA is applied to tune the antenna for maximum signal strength on-situ and in [12] and [10] the GA is used to tune the antenna over a large range of frequencies. Most of the work related to the RPMA is influenced by the encoding technique proposed in [15]. In this case the patch shape is decomposed into square pixels and a binary bit string defines the presence or absence of a pixel. This binary bit string acts as a chromosome in a GA formulation. Genetic algorithms are useful to explore poorly-understood search spaces. They are coded with the minimum of domain knowledge and assumptions, and use domain independent genetic operators to explore the search space. They can be very robust and persistent throughout the search but are very slow to converge to a result and are inefficient for local optimization. Systems that rely solely on the GA, therefore, require hundreds of iterations to reach their goals, as shown in [13] and [15].

The RPMA can be thought of as an artificial antenna designer in a constrained environment. Therefore developments in antenna CAD can be considered for adoption to reconfigurable antennas. Patnaik et. al. apply Neural Networks (NN) to reduce the design time of a reconfigurable 130^0 balanced bowtie antenna that can be described as a binary bit string of length 18 bits [16]. For the RPMA of fig.1(b), the equivalent chromosome length is 180 bits rendering this method computationally expensive. Several methods like pruning and structuring of the search space can be applied to improve the GA efficiency for CAD purposes. In [17], a Knowledge-Based Genetic Algorithm (KBGA) is developed to reduce the time required to evolve novel microstrip antennas. The KBGA selects antenna design heuristics (rules of thumb) that influence the genetic operators. The KBGA in [17] is hard-coded as a set of **if-then** rules and there is no provision for machine evolution of the rules.

In the case of the RPMA the various shapes that can yield the required characteristics are generally known and therefore a good proportion of the search space is known, fig.2 is evidence of this. The fixed antenna feed and the discrete nature of the shapes do however make the problem a formidable one, and require algorithms that can perturb the shape rather than the values of the geometrical dimensions. The changes in shape can be done efficiently by the application of domain knowledge, in the same way as human designers carry out the design task. In [18] shape-function grammars are proposed for use in antenna Intelligent Computer Aided Engineering (ICAE) software to model and synthesize microstrip antennas during the preliminary or conceptual stage of the design.In [1] a control algorithm that combines a search method with an approximate and fast to compute qualitative antenna model is proposed. Fig.3 is a block diagram of the proposed algorithm. The novelty in this algorithm is the addition of the approximate/qualitative model to the standard setup that consists of a search algorithm that operates with measured feedback, such as described in [13] and [14]. Referring to fig.3, the search algorithm receives inputs from the transceiver and consults the *approximate/qualitative model* to obtain a valid shape that is likely to satisfy the inputs. Measured feedback is used to modify the shape or suggest a new shape. The *learning* option tunes the qualitative model if necessary. This approach mimics the informal and intuitive *cut and try* method used extensively by compact antenna designers. In this method the designer starts with a set of candidates derived with the help of an informal model. Guided by general antenna domain knowledge, the designer modifies the shapes in an iterative way to obtain the required electrical characteristics. At the end of the cycle the best prototype is chosen for production. The qualitative model should in general be inexpensive in computational terms and deals directly with shape and form. The choice of the search method depends on certain aspects. For example if the qualitative model is a crude one, a GA is appropriate, where as if the model yields a more accurate representation, then a neighborhood search algorithm should result in a more efficient system. In [1] a shape grammar model is combined with a random search and the performance of the algorithm is demonstrated on narrow-meander-line structures. In this paper the qualitative model is extended to generate and analyze wide-meander line patch antennas as well as shorted patch antennas.

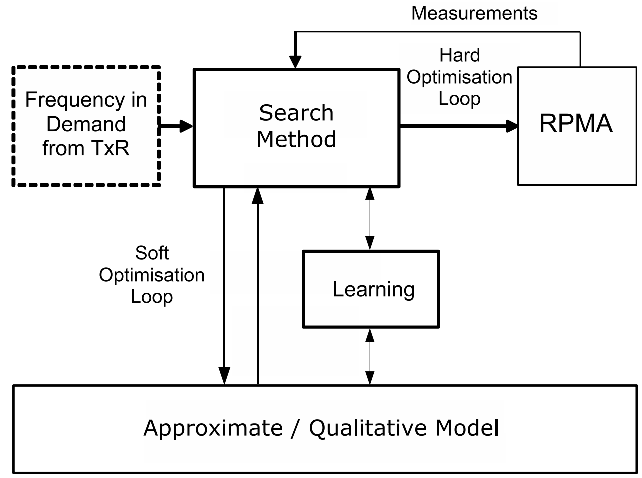


Figure 3. Block diagram for the algorithm modified from [1]. This algorithm introduces an approximate/qualitative model in the search loop.

III. THE GENETIC ALGORITHM IN CONTROL OF THE RPMA

The Genetic Algorithm (GA) is currently the standard method for tuning a RPMA as discussed in section II. In this section the Genetic Algorithm (GA) is used in search of shape configurations that yield the required frequency. Two types of Genetic Algorithms are coded. The first is a traditional GA and the second is a GA with a pruning mechanism that prunes out candidates that are highly unlikely to yield the target values. The results in this section are compared to results obtained using the shape-grammar based algorithm in section IV

A. The Genetic Algorithm

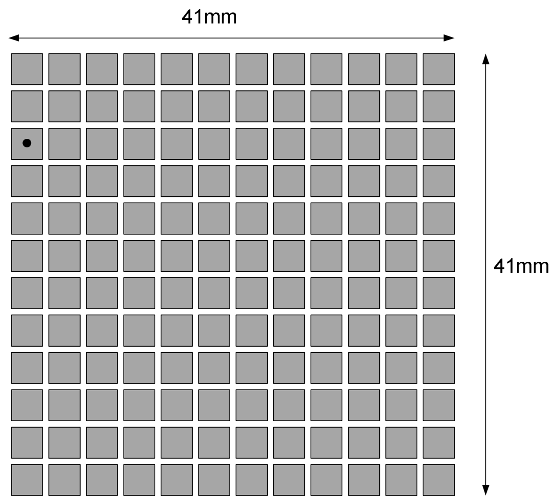


Figure 4. General structure for the Reconfigurable Pixel Microstrip Antenna for the GA experiments.

In this subsection the GA is used to investigate the search space of the reconfigurable pixel antenna. The goal is to investigate the number of generations or iterations required to find a shape that yields the given resonant frequency. A 12×12 RPMA is adopted for this experiment and each pixel is $3.41 \times 3.41mm$ in size. The pixels can be switched on and off to create the desired shape. The state of the pixel is coded as a '1' or a '0' in the GA chromosome. This encoding technique is first described in [15]. Fig.4 shows the structure of the reconfigurable antenna. In a practical reconfigurable antenna one would represent the switches in the chromosome, but this would end up in doubling the length of the chromosome and will not benefit this experiment. The total length and breadth of the antenna is $41 \times 41mm$. The radiating element is suspended in free space $3mm$ above the ground plane and has a nominal resonant frequency of $3.3GHz$. The GA was designed with a crossover probability of 0.7 and an exponentially decreasing probability of mutation. At the start of the GA run, the mutation rate is 0.01 and decreases to a constant 0.001 by the 10^{th} generation. The GA was coded in C# and coupled with CST Microwave studio using Object Linking and Embedding (OLE). The fitness function is a function of the resonant frequency and return loss. As the structure resonates nearer to the target frequency the fitness score increases exponentially. For a return loss less than $-10dB$ an exponential fitness function was used, for a return loss higher than $-10dB$ the fitness score is a constant. Thus a structure with a resonant frequency near the target and a high degree of matching is considered to be very fit and has a higher probability of reproducing. Roulette wheel selection, that considers all individuals, is used to select the next population. The chromosome length is 143 bits, given that the feed pixel is permanently 'ON'. A population of 40 chromosomes is chosen as a good tradeoff between a suitable population size and computational time necessary to complete a population run. The GA was given 4 target frequencies to reach as shown in Table I.

Table I
PERFORMANCE FIGURES FOR THE GENETIC ALGORITHM

Target Frequency / GHz	Final Frequency / GHz	Population Runs	Number of Configurations
3	3.01	10	400
2	2.08	70	2800
1	1.70	70	2800
0.7	1.70	70	2800

The GA is most successful for the $3.0GHz$ case. It manages to find a solution by considering 400 candidates. This case is close to the nominal resonant frequency of $3.3GHz$. The results agree with results in [15] and [19], were the target frequencies are close to the nominal resonant frequency. The $2.0GHz$ case is also successful although the number of candidates considered is now 2800. On the other hand the GA finds it very difficult to find suitable antenna configurations as the target frequency got smaller. For the $1.0GHz$ and the $0.7GHz$ target frequencies the GA fails to find a solution after considering 2800 candidates. Fig.5 shows the best structures that the GA delivered for the successful frequencies. For smaller frequencies more pixels had to be switched off, in order to lengthen the path. The path length needed for resonance at a lower frequency is longer than that required for a higher frequency and the GA has to search for a longer time to get closer to a good shape. The GA performance therefore does not scale well with frequency.

B. Pruning the GA Search Space

The second experiment introduces a pruning mechanism that improves the convergence of the search, with special consideration to low frequency targets. The idea is to eliminate those individuals that are highly unlikely to contribute towards reaching the goal. To perform such

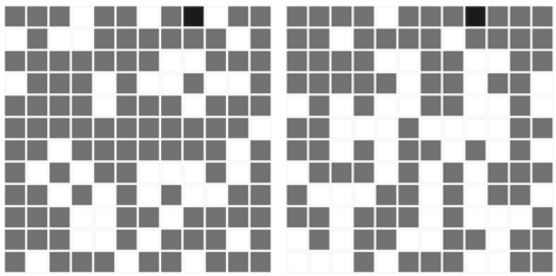


Figure 5. Best individuals found by the GA for the 3.0GHz and 2.0GHz cases.

pruning an approximate model is required. The chromosome is converted into a graph and the path from the feed to each pixel is calculated. A breadth-first search algorithm is used to find the path lengths from the feed position. The resonant frequency of the antenna is controlled by the length of the path between two potentially radiating edges and structures with a long pixel length are preferred for the next generation. Additionally during the process of selecting the next generation offsprings that are characterized by a path length that is similar or larger to the average length of the previous population are preferred. This was done to push the population towards structures with longer path lengths. The GA with the pruning mechanism was tested at a target frequency of $1.0GHz$. Table II shows a comparison of the results with and without pruning. The results show a marked improvement in computational time but the GA still finds it difficult to converge to the required result. This is an indication that the pruning model is not adequate.

Table II
PERFORMANCE FIGURES FOR THE GENETIC ALGORITHM WITH AND WITHOUT PRUNING

Pruning	Target Frequency / GHz	Final Frequency / GHz	Population Runs	Number of Configurations
No	1	1.7	70	2800
Yes	1	1.52	40	400

C. Conclusions from GA experiments

The GA converges for frequencies that are 60% or higher than the nominal frequency. There are various reasons why the GA fails to achieve the objective. An antenna will resonate at the lowest frequency along the longest path. If the crossover operation or the mutation operation does not modify the longest path, then the offspring will not be an improvement on its parents. The probability of the latter occurring is quite low if the reconfigurable antenna is encoded into a long chromosome. In summary the GA has difficulty in evolving longer winding paths that can support the lower resonant modes. The number of iterations to converge to the target can be effectively reduced by pruning the search space. The choice of pruning algorithm influences the subset of shapes searched by the antenna. In this case where the pruning algorithm looked for the longest paths the GA was then constrained to search in that subspace. The failure in finding low-frequency compact structures can therefore be attributed to an inefficient or incompatible encoding technique. What is required is an encoding technique that deals directly with shape.

IV. THE COUPLED RANDOM SEARCH - SHAPE GRAMMAR ALGORITHM

The discussion in this section is grounded on the goal to develop an algorithm that can efficiently tune the RPMA over the range of mobile frequencies that span from a few hundred MHz to a few GHz. The problem is formulated as a search for a patch shape that yields the required frequency of operation, while minimizing the amount of hardware switching taking place. Referring to fig.3, the search method and the approximate/qualitative model are implemented with a random search method and a shape grammar with feedback model. Fig.6 shows a system diagram for the algorithm. The search algorithm receives inputs from the transceiver and instructs the *shape grammar model* to suggest a valid shape that is likely to satisfy the inputs. At this point in time the search method accepts or rejects the suggestion, depending on whether it falls or not within a specified range (soft loop). If accepted the candidate is hardware switched and measured feedback is used to accept the candidate or reject it (hard loop). This random search works on the premise that the accuracy of the shape grammar model is within the acceptance range and the designs are therefore close to the intended targets. As used here the shape grammar model reduces the global search problem to a local random search. Experiments show that within $10 - 30$ iterations a solution is found. The rests of this section describes shape grammars in general and the RPMA shape grammar model. Finally the algorithm is evaluated and demonstrated with three examples.

A. Shape grammars

Shape grammars have been originally developed to generate architectural designs and art works that pertain to a particular style [20], [21]. Architectural designs are characterized by a well-defined function-shape decomposition such that the generating engine first satisfies the functional requirements and then proceeds to generate the physical shapes in a particular style. However compact microstrip antennas, like many engineering artifacts, do not have such a straightforward shape-function decomposition and instead

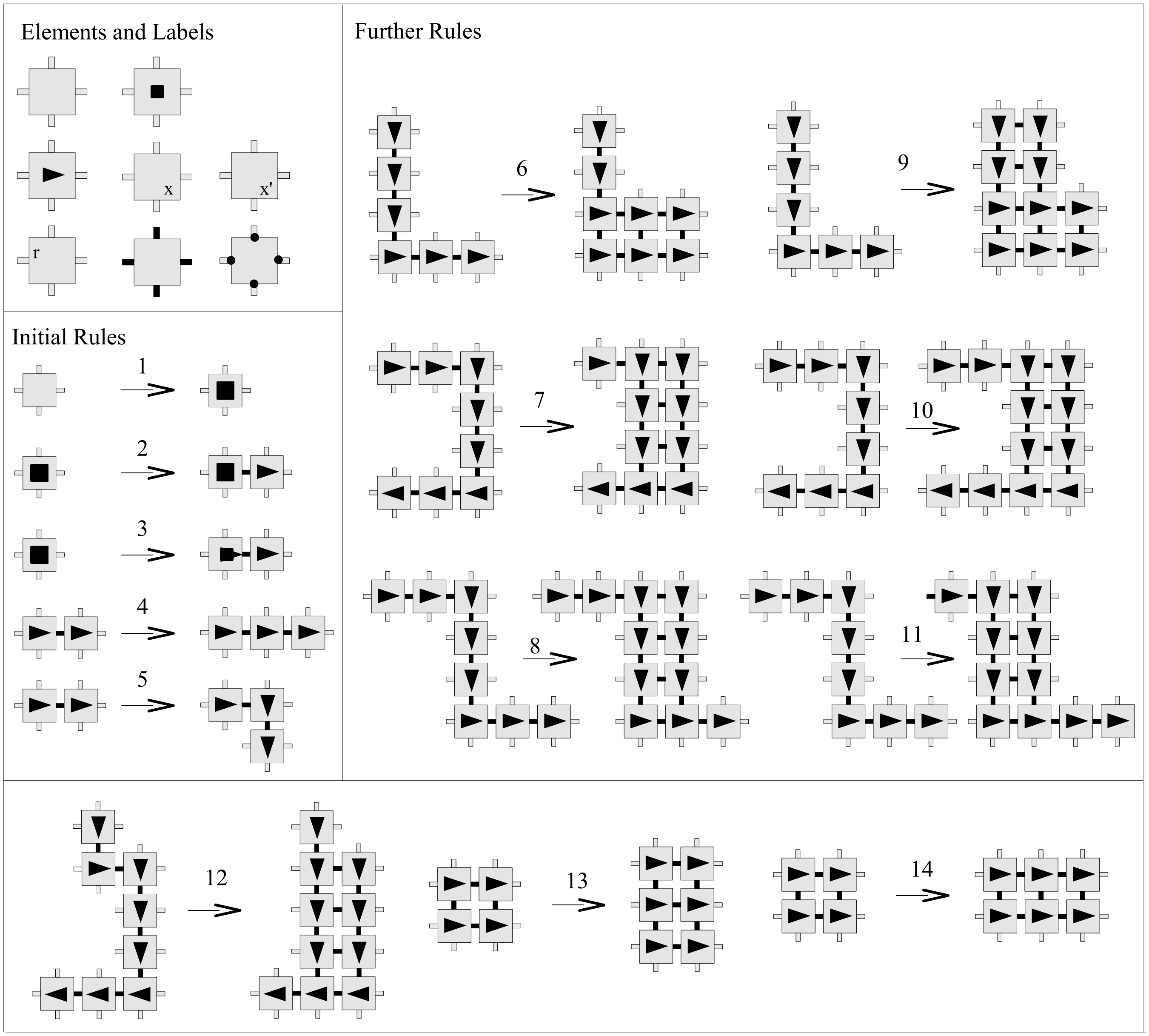


Figure 7. The reconfigurable pixel antenna shape grammar. This grammar produces shapes that are intended to operate at the fundamental mode of resonance.

exhibit a strong function-shape coupling, such that a small change in the topology or form can result not only in a significant change in performance, but can also render the design invalid. Agarwal and Cagan[22] propose shape grammars as a new framework for geometry-based engineering expert systems and express their belief that it is the class of products characterized by a strong function-shape coupling that stand to gain most from formal design tools because the lack of a pre-defined generation sequence limits human designs to only a small set of valid configurations.

In [23] a coupled shape-function grammar is proposed for the design of micro-electromechanical resonators. This is used to generate designs that function as resonators. The functional requirement is enforced by making sure that the grammar includes all the necessary elements that are required for the device to function and validity is ensured in this respect. The form of the device is then altered by choosing the rules at random or through a search process. This grammar does not include any feedback and this means that the design generated may not necessarily meet or be close to meeting all the required specifications for the intended applications.

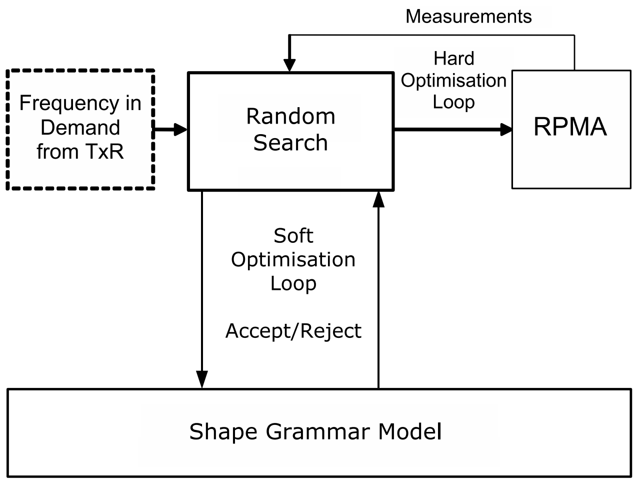


Figure 6. Block diagram for the control algorithm based on a random search method and a shape grammar model.

On the other hand, the microstrip antenna shape grammar described in [18] which is intended to be used as a generative engine that helps the antenna designer generate and combine shapes during the first phase of the design process, does include a feedback mechanism. This feedback consists of a transmission-line-model formula coupled to the shape attributes to approximate the frequency of operation and the input impedance.

B. The pixel antenna shape grammar

In this paper the microstrip shape grammar described in [18] and extended in [24] is modified to suit the RPMA. Fig.7 shows the RPMA antenna shape grammar. The grammar is a discrete and labeled 2D grammar. A shape grammar consists of four components; the initial shape, a finite set of shapes, a finite set of symbols and a finite set of shape rules. The basic shape is the square pixel with four switches, one on each side. Rectangles emerge and combine from the union of adjacent pixels. The grammar evolves a shape as two labeled branches or paths coming out of the probe feed or a shorting post. The paths formed are thus composed of cascaded rectangles. The grammar ensures that no branch overlaps or touches another branch and there are no loops along one path. This setup is suitable to model structures resonating at the fundamental mode, including shorted patch structures.

Fig.8 shows some examples generated by the grammar. The initial shape of fig.8(a) is evolved by applying the initial rules. The application of the initial rules (*rules 1 to 5*) generate a one-pixel-wide antenna shape. Referring to fig.8(a) the first rule applied is *rule 1*, followed by *rule 3*. *Rule 1* defines the first pixel as the location for the antenna feed port. *Rule 3* defines the first branch. This branch is evolved further by successively applying *rules 4, 5, 4, 4, 5 and 4*. The second branch is defined by first applying *rule 2* to the feed pixel and further evolved with a double application of *rule 4*. The labels in fig.8 are not all shown for clarity. Fig.7 defines the different labels. The black square defines a feed pixel. The black arrow indicates the direction of a path starting from the feed pixel through to the end of the path, indicating which switch is next turned 'ON'. The 'x' label is the path label. So for two paths there are two path labels, for example 'x' and 'y'. The path label is primed along the path and not primed at the end of the path. Thus the arrow and the path label allow an algorithm to follow the path. Rectangles are formed by switching an array of switches. The symbol 'r' is a unique integer number given to an emergent rectangle as defined by the shape rules. The black dot label defines the interface between rectangles. These labels are used by the algorithm that manages the generation of the shape and to calculate the effective end to end path length, which result is used for the approximate formula model. Fig.9 shows a fully labeled case generated by the application of the *initial rules*.

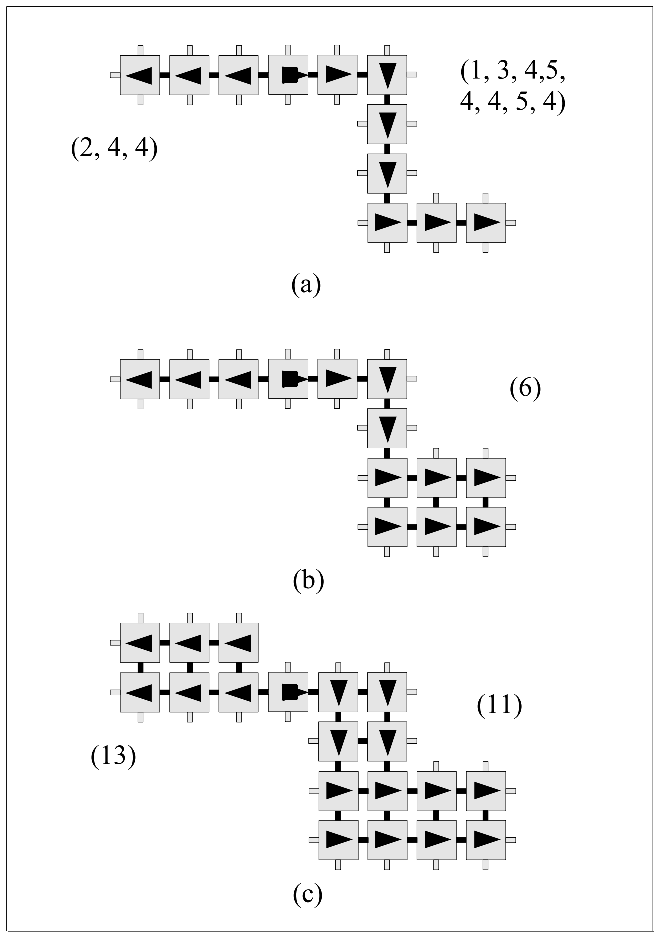


Figure 8. Examples of shapes generated by the grammar of fig.7. The rules applied are shown in brackets at the side of each branch.

The structure is further evolved by the application of the *further rules* given in fig.7. The structure of fig.8(a) is considered as an initial shape. The rules (6 to 12) can be either chosen at random or via a rule selection algorithm. In this experiment priority is given to evolving the path ends and followed by sections closer to the feed. Fig.8(b) depicts a structure derived using such a rule selection algorithm. In this case *rule 6* is applied. Applying *rule 11* to the branch on the right and then *rule 13* to the branch on the left results in the structure of fig.8(c).

Furthermore standard shapes, like the L-shape and C-Shape, can be defined by a subset of rules, including a limit on the number of certain rule instances that can be applied. In this way the control algorithm can test whether for example an L-shape fits for a given frequency, given that the feed position is defined. Additionally the line grammar is implicitly used to explore the design space and therefore takes into consideration other concurrent shapes when multi-feeds are present.

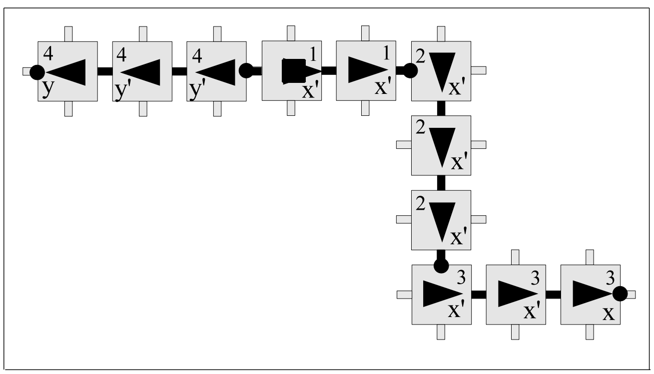


Figure 9. A labeled structure evolved with the initial rules.

As discussed in section III the qualitative model should deal directly with shape and develop a candidate in a rather formalized way. The RPMA shape grammar fulfills this requirement. The shapes generated consist of one feed and two non-touching branches. The feed is at a fixed position while the branches can take any shape. To generate a shape the grammar starts from the feed and evolves two branches that can take any path, subject to constraints. Additionally the shape grammar can perturb a shape in an apparent smart way, mimicing the action of a human being who applies knowledge to find a solution.

C. Approximate Analysis

The shape grammar model relies on the capability of being able to carry out an approximate analysis of the structure. Labels are given to rectangles, paths, feed points and radiating edges. These labels and their positions are used to obtain the shape attributes; length and widths of rectangles, path length from feed to radiating edges or path ends and the presence and location of shorting posts and feeds. The shape attributes are then used to approximate the electrical characteristics (frequency of operation and input impedance) that are used as feedback by the rule selection algorithm. The quantitative relationship between the shape attributes and the electrical characteristics is described by a formula based on the transmission line model.

The resonant frequency depends on the length of the current path as well as on the degree of *meandering*. A function derived from the transmission line model (modified from [18]) is used to obtain an approximation for the resonant frequency in GHz, eqn.1.

$$f_0 = 300/2(L_e + (2a_0 + a_1 NC)L_p) \tag{1}$$

where L_e is the effective path length in mm, NC refers to the integer number of corners along the path and L_p is the width of the pixel in mm. L_e is the end-to-end distance obtained by joining the midpoints of the rectangle edges along the path, as shown in fig.10. The coefficients a_0 and a_1 are fitted with a training set obtained from measurements, which in this study is substituted by a full-wave FDTD model [25]. For the structure of the RPMA shown in fig.1(a) these coefficients are manually optimized using a training set for the lower frequency bands, $a_0 = 0.55$ and $a_1 = -0.02$. The lower frequency band was chosen since, as previously shown, is the most challenging for a search algorithm.

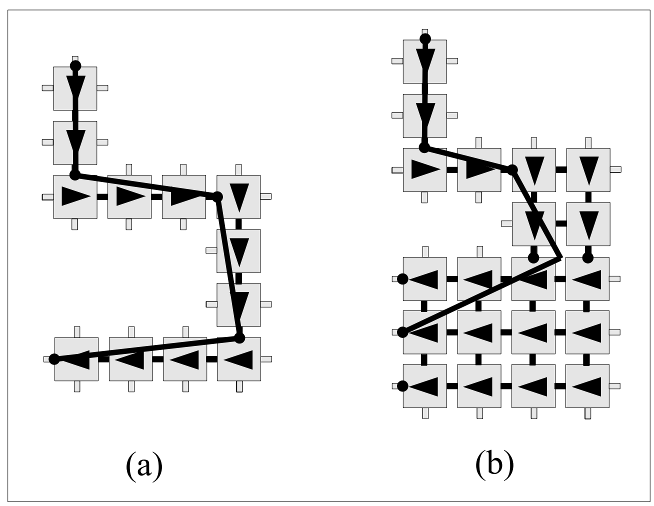


Figure 10. Evaluation of the *effective length*.

The driving point impedance depends mostly on the relative position of the feed point along the current path. The model does not yield a numerical value for the input impedance or input reflection coefficient but gives an indication of how far away it is from 50Ω, the system impedance. The input impedance estimate is obtained by considering the ratio of the effective length for branch 'x' and the effective length for branch 'y', ($L_x : L_y$). From experiments it is concluded that a good match is obtained when the ratio $L_x : L_y$ is in the range of 0.7 to 0.85.

Furthermore the $L_x : L_y$ ratio value as well as a_0 and a_1 in eqn.1 can be tweaked by the learning method shown in fig.3 with measured feedback.

D. Evaluation Methodology and Results

The effectiveness of the control algorithm in achieving the targets desired is demonstrated on three cases (a) pixel-wide meander-line shape resonating at $1.3GHz$, (b) wide meander-line shape at $1.8GHz$, and (c) shorted wide-meander-line shape at $0.9GHz$.

For the first experiment a 10×10 pixel antenna is assumed. The total size of antenna patch is $41mm \times 41mm$ and the size of each pixel is $3.6 \times 3.6mm$. The height of the substrate (ϵ_r=1.0) is $3.0mm$. Eight candidate pixel-wide meander-line shapes that resonate at $1.3GHz$ are generated using *Algorithm Synthesize A*, fig.11, which together with the *shape grammar rules* is encoded into C++ code. The candidates generated are then simulated with an FDTD model, which is used as a benchmark and replaces measurements. The closest candidate to the required resonant frequency is chosen. Table III shows the resonant frequencies and errors for these eight candidates under the set of columns *Set A*. Candidate *#1* is the closest to $1.3GHz$ with a target error of 0.143%. The bandwidth of such an antenna is approximately 3% and therefore this candidate is valid. This selection task is carried out by the *random search* method. If no shape satisfies the requirements then the search method requests more candidates and repeats the process. The same results can also be used to tune the model coefficients. Table III shows a second *set B*, where the best candidate is off the frequency mark by 0.263%. Fig.12 depicts these two candidates. This result demonstrates how effective a grammar based qualitative model can be in reducing the number of switching iterations required.

Table III
RESULTS SETS A AND B

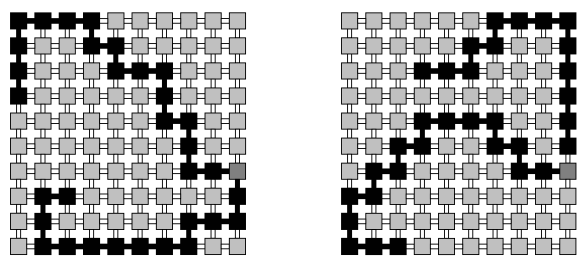
#	Freq Model (Set A)	Freq FDTD (Set A)	Target Error (Set A)	Freq Model (Set B)	Freq FDTD (Set B)	Target Error (Set B)
0	1.286	1.232	5.248	1.265	1.323	1.736
1	1.296	1.298	0.143	1.292	1.261	3.011
2	1.292	1.243	4.353	1.265	1.224	5.837
3	1.282	1.335	2.686	1.295	1.236	4.952
4	1.279	1.345	3.475	1.276	1.277	1.755
5	1.268	1.260	3.056	1.292	1.240	4.600
6	1.292	1.272	2.128	1.289	1.303	0.263
7	1.262	1.315	1.126	1.292	1.259	3.164

In the second experiment the quest is a patch shape resonating at $1.8GHz$. The antenna is a 12×12 pixel structure and the total size of the square antenna patch is $41mm \times 41mm$ with a pixel size of $2.9mm \times 2.9mm$. The patch is at a height of $3.0mm$ above the ground plane. The candidate shapes are generated using the full grammar and the algorithm is given in fig.13. For this run the coefficients are tweaked to $a_0 = 0.6$ and $a_1 = -0.1$. Table IV lists the first 30 candidates in the run. The model formula is less accurate in this case and therefore on average a greater number of candidates is necessary for the algorithm to converge. The best candidate is off the frequency mark by 0.556% and for this case occurs at the 25^{th} iteration. These two candidates are shown in fig.14.

In the third experiment the quest is a patch shape resonating at $0.9GHz$. The antenna is a 10×16 pixel structure and the total size of the square antenna patch is $26mm\times41mm$ with a pixel size of $2.05mm \times 2.05mm$. The patch is at a height of $3.0mm$ above the ground plane. The candidate

```
01  Set frequency of resonance and desired input
    impedance;
02  Start Synthesis
03  Define feed position, rule 1;
04  Define branch 'x', rule 2;
05  Define branch 'y', rule 3;
06  Obtain an estimate for the input impedance;
07  If the input impedance estimate is greater than the
    target, extend the shortest branch from the set x,y,
    rules 4 or 5; if branch is not extensible goto line 10;
08  If the input impedance estimate is less than the target,
    extend the longest branch from the set x,y, rules 4
    or 5; if branch is not extensible goto line 10;
08  Obtain an estimate of the resonant frequency;
09  If frequency estimate is greater than the target value
    goto line 06;
10  End Synthesis
11  Return estimate of resonant frequency and input
    impedance;
```

Figure 11. Algorithm Synthesize A: Generates meander-line elements whose width is equal to one pixel.



(a) (b)

Figure 12. Best candidates in set A and B.

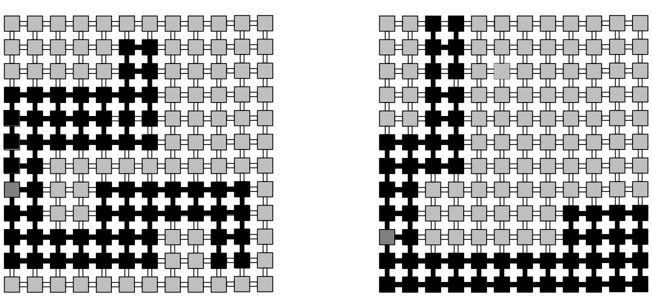
```
01  Set frequency of resonance and desired input impedance;
02  Start Synthesis;
03  Call Algorithm Synthesize A to generate an initial shape;
04  Define and reset subsetFlag to FALSE;
05  For Each branch from the set x,y do
06  {
07  For Each rectangle along a branch (starting from the end) do
08  {
09  Build a subset of applicable rules from the set 6 ... 13;
10  If a subset is not NULL set subsetFLAG to TRUE;
11  Choose a rule from the subset and apply it with a probability of Pa = 0.8;
12  }
13  }
14  If subsetFLAG == FALSE goto line 16;
15  Goto Line 04 with a probability of Pr = 0.7
16  End Synthesis
17  Obtain an estimate for the input impedance;
18  Obtain an estimate of the resonant frequency;
19  Return estimate of resonant frequency and recomputed input impedance
```

Figure 13. Algorithm Synthesize B: Generates meander-line elements whose width is greater than one pixel.

shapes are generated with the full grammar, as in fig.13, and in this case a shorting post is added. Equation 1 is therefore adjusted to,

$$f_0 = 300/4(L_e + (2a_0 + a_1NC)L_p) \tag{2}$$

Table IV lists the first 30 candidates in the run. The best candidate is off the frequency mark by 0.889% and for this case occurs at the 19^{th} iteration. These two candidates are shown in fig.15.

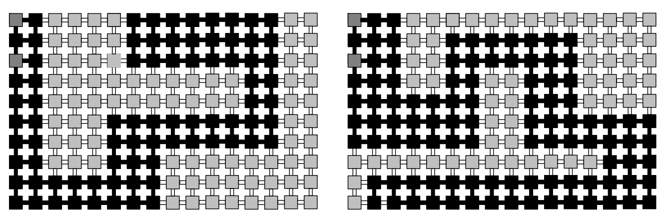


(a) (b)

Figure 14. The best two candidates resonating at 1.8GHz.

Table IV
CANDIDATES FOR THE 1.8GHZ SET AND THE 0.9GHZ SET

		1.8GHZ Set			0.9 GHz Set	
#	Freq Model	Freq FDTD	Target Error	Freq Model	Freq FDTD	Target Error
0	1.774	1.755	2.481	0.912	0.928	3.089
1	1.817	1.858	3.228	0.889	0.873	2.997
2	1.866	1.871	3.962	0.914	0.950	5.559
3	1.856	1.914	6.327	0.936	0.957	6.300
4	1.774	1.751	2.716	0.989	1.023	13.619
5	1.764	1.692	6.025	0.855	0.848	5.767
6	1.787	1.828	1.542	0.937	0.881	2.109
7	1.908	2.088	15.982	0.937	0.999	11.016
8	1.742	1.637	9.030	0.918	0.982	9.074
9	1.831	1.890	5.006	0.851	0.878	2.446
10	1.805	1.827	1.527	0.833	0.936	3.953
11	1.789	1.730	3.911	0.936	0.850	5.527
12	1.705	1.688	6.244	0.894	0.918	1.963
13	1.815	1.775	1.388	0.823	0.861	4.389
14	1.892	1.785	0.833	0.967	0.925	2.747
15	1.723	1.605	10.807	0.959	1.033	14.752
16	1.750	1.638	8.976	0.827	0.748	16.943
17	1.875	1.723	4.271	0.884	0.879	2.385
18	1.806	1.864	3.558	0.884	0.863	4.157
19	1.856	1.757	2.381	0.831	0.892	0.889
20	1.914	2.019	12.152	0.894	0.878	2.456
21	1.786	1.819	1.040	0.892	0.877	2.508
22	1.735	1.523	15.372	0.912	0.952	5.830
23	1.951	1.763	2.029	0.862	0.824	8.445
24	1.781	1.560	13.345	0.864	0.853	5.273
25	1.975	1.810	0.556	0.877	0.923	2.512
26	1.930	1.936	7.562	0.982	0.951	5.680
27	1.806	1.896	5.340	0.835	0.810	10.014
28	1.822	1.778	1.196	0.928	0.884	1.778
29	1.772	1.994	10.766	0.876	0.766	14.853



(a) (b)

Figure 15. The best two candidates resonating at 0.9GHz.

V. CONCLUSIONS AND FURTHER WORK

A novel algorithm that is based on a shape grammar model and a random search is proposed for the efficient control of the reconfigurable pixel microstrip antenna (RPMA). The shape grammar is coupled with formula transmission line models to generate shapes that are valid in terms of frequency of operation as well as input impedance. The shape grammar is intuitively derived from microstrip antenna design knowledge. The shape grammar is most useful in generating irregular meander-line antenna shapes commonly exploited in compact antennas. The performance of the algorithm is demonstrated on three prototypes and is compared to a Genetic Algorithm (GA) with and without a pruning mechanism. The proposed control algorithm outperforms the GA by a factor of 100 and by a factor of 10 when the pruning mechanism is switched on, in the terms of the number of iterations required to converge. Furthermore the algorithm scales well as the frequency of operation decreases, whereas the GA does not.

The experiments reported in this paper highlight the fact that the transmission line models adopted for the approximate analysis of a shape are most accurate for the pixel-wide meander-line examples. As the shape is modified via the further rules the accuracy degrades. This is the reason why more iterations are required for the wider lines. The width of the line has an effect on the input impedance and to a lesser extent on the frequency of resonance. Furthermore the width of the line is not a constant, but varies. Some improvement can be obtained by re-tuning the coefficients, but in general a formula model that takes into consideration the widths of various sections may perform better. Additionally it may be useful for the algorithm to be able to learn on the accuracy of the model and predict the number of iterations required. Further work is required to verify the performance of such models.

The demonstration in this paper is carried out using a random search, where the search method obtains a candidate from the shape grammar, and based on measured results accepts or rejects the candidate. This process continues till an acceptable solution is found and there is no attempt to modify the shape based on immediate measured feedback. It will be interesting to see whether the inclusion of such a shape annealing mechanism results in less iterations.

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