11

A Microstrip Antenna Shape Grammar

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1. Introduction

In this chapter a microstrip antenna shape grammar is described and its use is demonstrated as a design tool for compact microstrip antennas and in the real-time control of reconfigurable pixel microstrip structures. The microstrip shape grammar formalizes the cut and try methodology used widely by microstrip antenna engineers, who make use of rules of thumb, simple formula models and intuition to combine and manipulate various patch shapes that yield the required characteristics. Simple formula models linked to shape attributes are developed to provide immediate feedback to the shape evolution process and microstrip patch shapes whose electrical characteristics closely match the required specifications are generated. The machine can therefore explore a wide variety of configurations in a relatively short time.

2. Compact microstrip antennas

Compact microstrip antennas are devices that are small in size, but at the same time exhibit electrical characteristics that are similar to those enjoyed by antennas of standard size. More specifically the electrical length of compact antennas is similar to that of a standard antenna. Fig.1(a & b) are two typical examples of compact multi-band antennas, where the non-standard shapes of the microstrip patches are mainly responsible for the electrical characteristics exhibited by these structures. The structure of fig.1(b) is an evolution of the design in fig.1(a), which is modified to accommodate a third element in the same space. The design process for these two prototypes is not obvious and difficult to formalize. Additionally, the positions of feeds are often fixed by the overall system considerations and the antenna designer has to work out the shape around these fixed components. Compact antennas are also characterized by a strong coupling between the electrical characteristics and the physical composition of the structure and a small change in the topology usually results in an invalid design. A significant amount of design time and effort is therefore invested in developing these antennas.

An antenna that can be switched between wide-band and narrow-band operation is shown in fig.1(c). The synthesis task for this case is equally, if not more, difficult to formalize and the designer has to develop patch shapes that when connected together via switches yield the required electrical properties.

Fig.1(d) shows a pixel reconfigurable antenna. This structure consists of an $M \times N$ matrix of small metal patches, or *pixels*, interconnected with electronic switches. When all switches are switched *ON* the structure behaves like a rectangular patch. When some of the switches are turned *OFF*, the electrical current path is modified and therefore the electrical characteristics are altered. A single device can therefore, configure itself to operate over a wide frequency

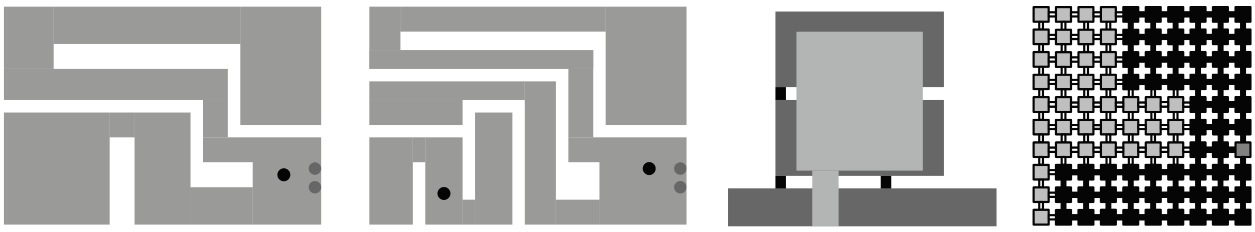


Fig. 1. Compact microstrip antenna designs (a) Dual-Band single feed, (b) Tri-band with two separate feeds, (c) a structure that can be switched from wide-band to narrow-band operation, from (J. R. Kelly et al.,2008), and (d) a pixel microstrip reconfigurable structure.

range, optimize the signal strength and change polarization in a short period of time as demanded by the system. The delivery of such devices certainly means a change in the way antennas are designed and deployed. Most of the research effort to-date on reconfigurable antennas has been targeted towards the hardware issues, ((B. A. Cetiner et al.,2004) and (A. Grau and Lee Ming-Jer et al.,2007)) and the development of efficient control algorithms still needs to be adequately addressed. The switching operation is equivalent to altering the shape of the patch and the skills required to carry out this task are similar to the expert skills exhibited by compact antenna designers. It is therefore expected that algorithms proposed for the control of reconfigurable pixel antennas closely follow those studied in the automation of the synthesis task in compact antenna design.

3. Microstrip antenna CAD

The design of compact antennas is a process that iterates between two phases. The first phase is essentially a manual task, where the antenna engineer selects, combines and fits in a constrained volumetric and electromagnetic space, a number of geometric shapes that together yield the desired electrical characteristics. During the second phase the engineer makes extensive use of numerical Computer Aided Design (CAD) tools to refine and tune the initial design. Much research effort has focused on CAD for the second phase and very little has been done in developing antenna CAD for the first phase. These designs are therefore carried out by expert designers and modifying a structure to suit some additional specifications requires a significant time investment and effort. A CAD tool that formalizes some of the design processes would therefore help not only in the timely delivery of the product, but also in the exploration of novel structures.

Most of the research work carried out in the area of patch antenna CAD related to the first phase or the synthesis task considers meta-heuristic algorithms, such as the Genetic Algorithm (GA), Simulated Annealing (SA) and Tabu Search (TS). Systems or methodologies based on the GA are by far the most studied. GAs are search methods based on the *survival of the fittest* technique found in nature. Initially a large population of randomly generated designs (in this case antennas) is instantiated and each design is encoded as a *chromosome*. These designs, called *individuals*, are simulated and ranked according to how well they perform, or how *fit* they are. The next generation is constructed by first selecting two parents and then combining the designs or chromosomes together, in the same way as offsprings in nature are characterized by a chromosome that is made up from parts of the parents' chromosomes. Superior individuals are given a greater chance in the reproduction process, ensuring that the fitness in a population improves as the number of generations increases.

The evolutionary process continues until a design that closely matches the requirements is found. The performance of GAs depends mainly on two parameters, the *crossover* operator and the *encoding* of the chromosome. The *crossover* operator defines how two chromosomes are combined together to produce the offsprings, whereas the encoding techniques defines how a *real-world* design is represented as a string of symbols.
(J. M. Johnson et al.,1997) pioneered the use of the GA for machine evolved planar microstrip antenna shapes that exhibit wide-band characteristics. In this work a rectangular design space is defined in terms of a matrix of rectangular or square pixels. The entire patch shape is defined by the presence or absence of a pixel. The shape is therefore represented or encoded as a binary bit string of length $M \times N$, where each element of the string, or *gene*, defines the presence or absence of a pixel. The crossover operator is a straightforward single point crossover. In (N. Herscovici et al.,2002) the same encoding and crossover techniques are used in the search of compact microstrip antenna and a 30% reduction in size is obtained. Not surprisingly the GA has been applied to the control of reconfigurable antennas. In (D. S. Linden,2002) and (Zhang Min et al.,2004), the GA is applied to tune the antenna for maximum signal strength on-situ and in (Coleman,C.M. et al.,2000) and (L. N. Pringle et al.,2004) the GA is used to tune the antenna over a large range of frequencies. In (Adrian Muscat et al.,2010) it is shown experimentally that the encoding scheme described in (J. M. Johnson et al.,1997) fails to evolve compact structures of the types in Fig.1(a& b) and concludes that a different encoding scheme and corresponding crossover operator is required. Another drawback with a GA based search algorithm is the large number of iterations required to converge to a result. (E. A. Jones et al.,2000) proposed an encoding scheme for wire antenna arrays based on a language, defined by a set of rules that combine a set of components to generate wire antenna array configurations. A GA is deployed to produce designs in this language. The search space is therefore narrowed, rendering a more efficient search. In (Adrian Muscat,2002), a Knowledge-Based Genetic Algorithm (KBGA) is developed to reduce the time required to evolve novel microstrip antennas. The KBGA makes use of the abstract shape representation described in (J. M. Johnson et al.,1997) and selects antenna design heuristics (rules of thumb) to influence the genetic operators. The KBGA is similar to a set of design techniques, but does not deal directly with shape.
Furthermore, the design paradigms described above are required to call an accurate numerical model for each configuration developed and more importantly they do not link the topology of the shape to the electrical properties. They cannot therefore carry out a modification in the shape or topology in a logical way and thus cannot mimic reasoning and intuition, two important characteristics in design.

4. Shape grammars

Shape grammars consist of a finite set of elements and a finite set of rules that define how the elements are connected together to generate designs in the specified language. The rules applied can be either chosen by the human designer or by the machine through an algorithm. Shape grammars where originally developed in architecture to generate designs in a particular style, (G. Stiny et al.,1978) and (U. Flemming,1987). The functional requirements are first specified and then the generating engine generates physical configurations in a particular style. Shape grammars where later applied in civil and mechanical engineering such as in the design of optimal truss structures (K. Shea et al.,1997), and the design of coffee makers (Manish Agarwal et al.,1998).

(Manish Agarwal et al.,2000) then proposed shape grammars as a framework for the design of geometry-based engineering systems. The functional component of most engineering systems is strongly coupled with its physical and geometrical composition and a small change in the topology can result in a significant change in function and performance. This characteristic limits human designers to very few configurations. Therefore a formal design tool that is automated on a computational machine should be able to explore a much wider variety of configurations. (Manish Agarwal et al.,2000) demonstrated the concept by developing a coupled form-function shape grammar for the design of micro-electromechanical resonators. The grammar enforces the inclusion of all the necessary components for the device to function as a resonator. However, this does not guarantee that the device is close to meeting the specifications and the only way to know this, is through a numerical simulation, which is computationally expensive.

(E. A. Jones et al.,2000) developed a wire antenna array language that defines structure in the style of Yagi and log-periodic arrays and combines this with a genetic programming (GP) algorithm . The *antenna language* defines how wire dipoles, gaps, sources and transmission lines are connected to form antennas. A genetic algorithm, coupled with a numerical wire antenna model, uses this language to search for functional designs. As in (Manish Agarwal et al.,2000), many of the designs generated are invalid, and a time-consuming numerical model is required. This is however the first time a grammar based technique is applied to an antenna problem.

The shape grammar developed in (Adrian Muscat,2010) and described in this chapter uses immediate feedback to guide the shape evolution and avoids the problem of generating and numerically simulating invalid configurations. Feedback is obtained by analyzing the geometry of the 2D shape and linking the shape attributes to simple computationally inexpensive formula models. Shape analyzes is carried out by decomposing the shape into a chain of labeled rectangular shapes. The labels and the sub-shape attributes are used for the analysis. This paradigm is suitable to generate the first phase or initial design, which is then passed through an optimization process. Additionally, the microstrip shape grammar solves the problem of encoding compact microstrip shapes.

5. The microstrip antenna shape grammar

The microstrip antenna shape grammar generates shapes that fit in a 2D design space divided into square pixels. Two examples of design spaces are shown in fig.2(a), a rectangular design space, and fig.2(b), an L-shaped design space. Fig.2(c, d, e, & f) are examples of microstrip shapes generated on a 12×10 matrix of square pixels. The grammar rules described in this chapter evolve a shape as two labeled branches or paths coming out of the probe feed or a shorting post. The paths are composed of cascaded rectangles. The grammar ensures that no branch overlaps or touches another branch and there are no loops along one path. This grammar is suitable to model structures resonating at the fundamental mode, including shorted patch structures, that are the most common building blocks in the design of compact microstrip antennas. Figs.2(c) and (f) are shapes that can be evolved by this grammar, while figs.2(d) and (e) cannot be generated by this grammar.

The rest of this section is organized as follows: The grammar elements and rules are described first, followed by an explanation of the feedback mechanism. The grammar is then demonstrated in the design of a multi-band antenna and in the control of the reconfigurable microtrip antenna.

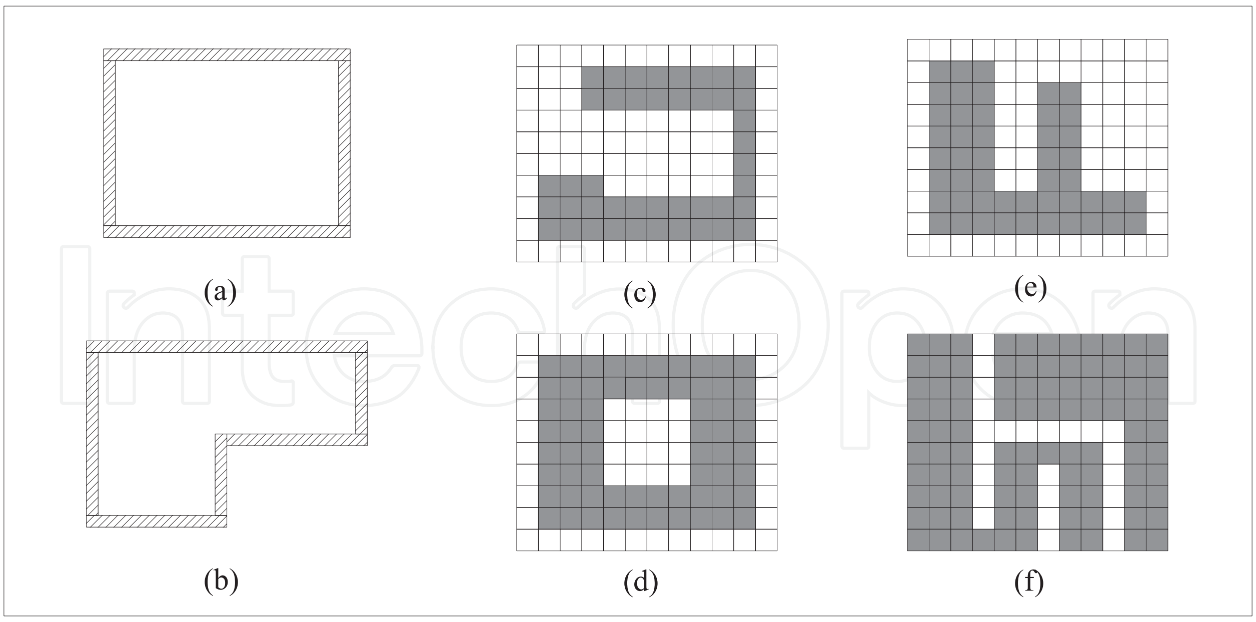


Fig. 2. (a) rectangular shape 2D design space, (b) L-shape design space, (c) to (f) Shapes generated over a matrix of square pixels. Examples (c) and (f) conform to shapes generated by the grammar described in this chapter.

5.1 The grammar elements and rules

Fig.3 shows the elements and the initial rules that define the initial patch shape, that consists of a probe feed and two narrow branches. The basic shape is the square pixel. Rectangles emerge from the union of adjacent pixels and more complex shapes emerge from the union of rectangles. Therefore as the shape evolves rectangles combine into new rectangles and the overall shape topology changes. Furthermore the pixels and rectangles are labeled. An integer number, label 'r', is given to an emergent rectangle. The arrow and diamond symbols define how the pixels are connected to form a rectangle. The arrows define the general direction of the electrical current and the diamonds define transverse paths. The labels are used during shape evolution as well as during analysis for feedback. As an example, fig.4(b) shows rectangles *1, 3, and 4* connected in cascade. The *dot* symbol defines the interface points in between rectangles. The *width* and *length* of each rectangle is used by the feedback mechanism. Finally the grammar rules ensure that the necessary components are not overwritten during the evolution of the shape. The microstrip shape grammar is therefore a 2D parametric, labeled and weighted grammar.

Fig.3 gives the first set of grammar rules. *Rules 1* to *4* are termed the *initial rules*. A configuration starts with a feed pixel that is defined by *rule 1*. *Rule 2* defines and labels the starting points for the two branches *a* and *b*. *Rule 3* attaches a pixel to one of the chosen edges and the first rectangle is defined. *Rule 4* attaches a pixel to the other chosen edge and the second rectangle is so defined. The latter rectangle is composed of two pixels. The initial shape thus comprises two branches, labeled *a* and *b*, and the labeled feed pixel. The radiating edges are defined at the end of each branch. The *line generation rules 5* to *7*, fig.3, are applied to evolve the starting shape. The rules define both the shape and label algebra, and prior to applying a grammar rule, the machine algorithm checks that the application of the rule does not violate a constraint.

To ensure a concise grammar two rule operators, the *ROTATE* and the *FLIP* are defined in fig.6. These operators transform rules to suit different orientations, and two examples on *Rule*

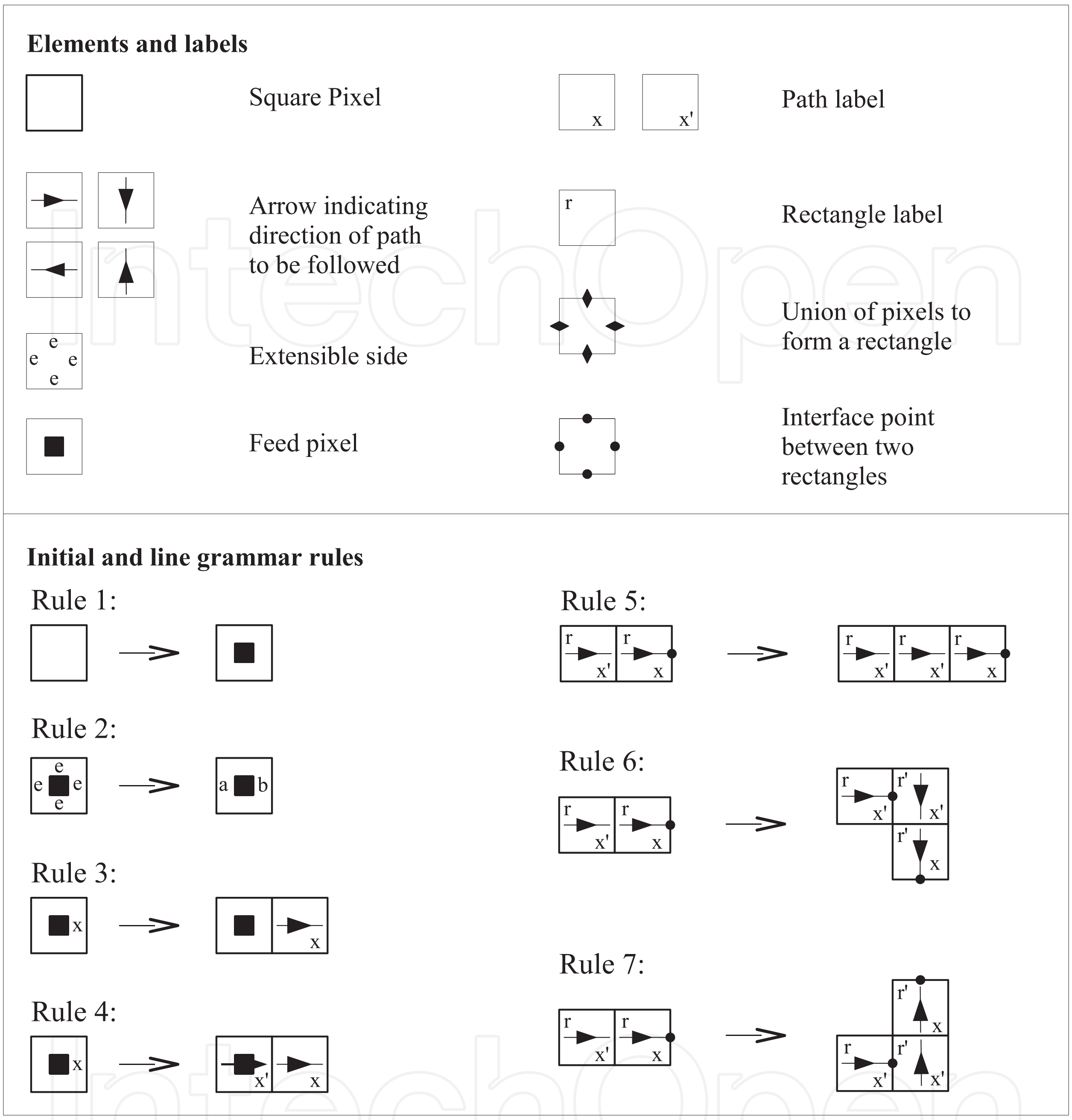
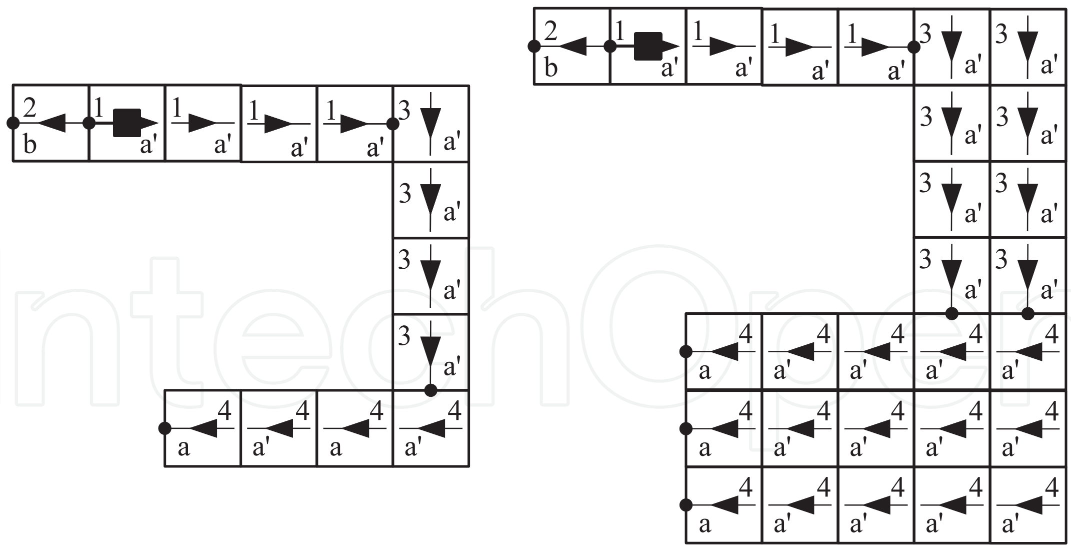


Fig. 3. The grammar elements and labels, initial and line grammar rules.

7 and *Rule 6* are given. The second example shows how in fact rules *6* and *7* are related with the *FLIP* operator.

In summary, the line grammar ensures that one feed is included, a maximum number of two branches are present, the width of the branches is equal to one pixel and the branches do not form loops. An example of a shape generated by the *line grammar* is given in Fig.5. The arrow label is very important as this indicates the current flow and subsequently the path. The line grammar generates one-pixel wide lines. To widen the rectangles or sub-shapes, the *extended grammar* is applied. The initial shape for the extended grammar is the final shape evolved with the line grammar rules. Another important objective of the *line grammar* is to explore the design space, taking into consideration other concurrent shapes as in multi-band designs. The



(a) (b)

Fig. 4. Two patch shapes decomposed into rectangles, ready for analysis.

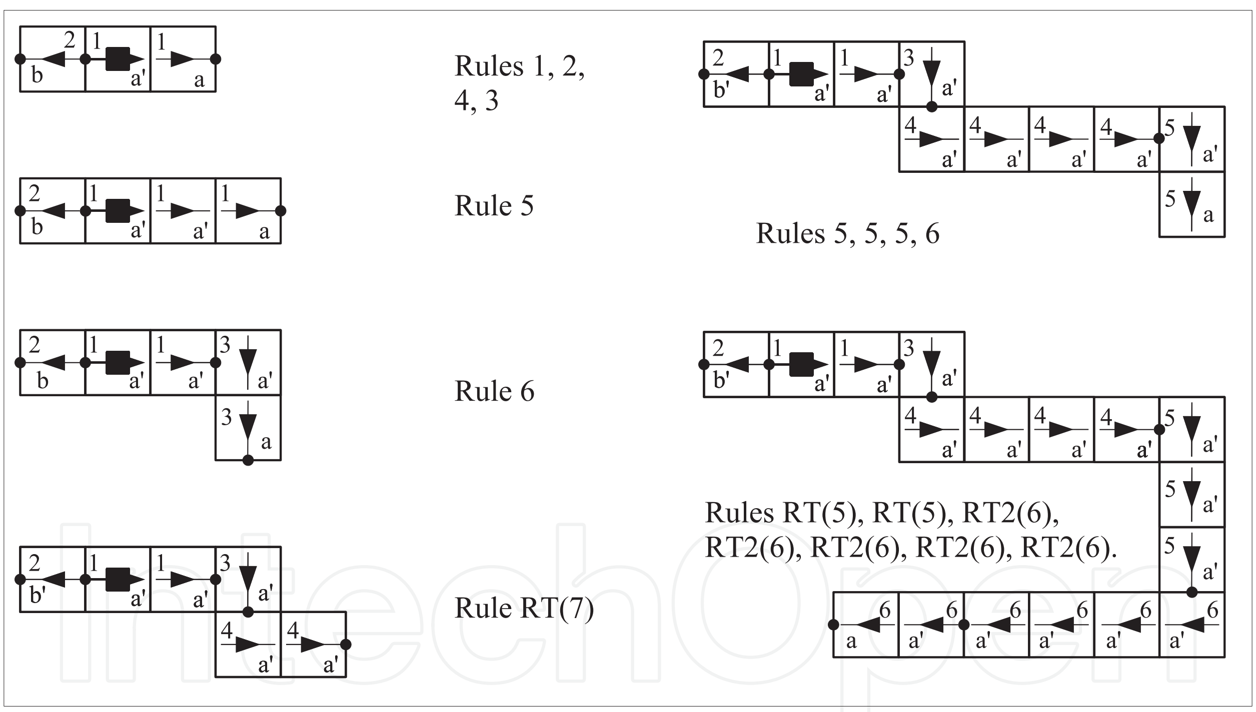


Fig. 5. A Shape generated by the grammar defined in fig.3.

final shape for the extended grammar is considered as a microstrip line defined by a chain of rectangles.

Fig.7 and fig.8 define the extended grammar *rules 8* to *18*. The rules are applied to widen arbitrary line sections and extend the line ends. *Rule 8, 9 and 10* in fig.7 define how the line in the vicinity and including the probe feed can be evolved. The application of the *FLIP* operator defined in fig.6 is useful to apply these rules to other orientations. *Rule 11* extends the branch ends, thus contributing to a longer current path, while *rule 12* widens the rectangle at the end of the branch. *Rule 13* is a special rule that does not change the shape, but changes the

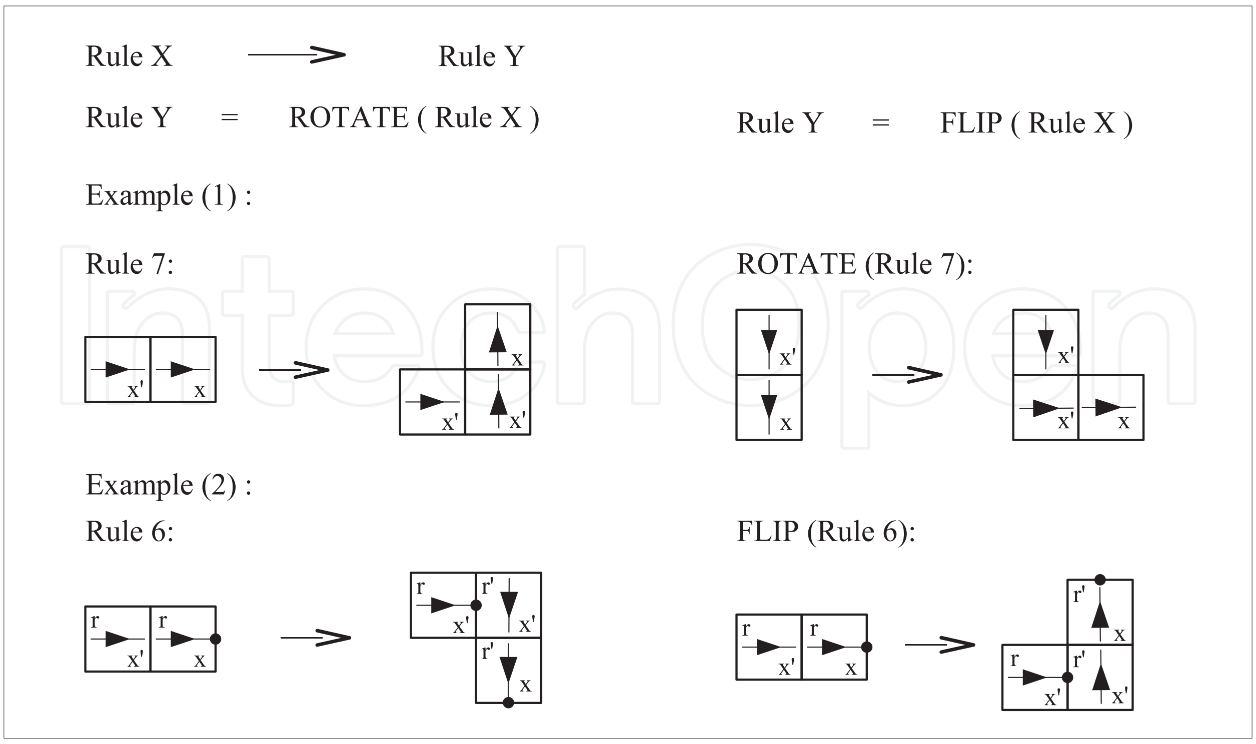


Fig. 6. Rule operators.

current direction along the rectangle at the end of the branch and therefore this rule is useful during analysis described in section 5.2. Rule 14 in fig.8 evolves a δ-bend into an L-shape. *Rule 15* widens the outgoing inside corner in an L-shape. *Rule 16* widens a straight branch from start to end, or a branch that consists of one rectangle. This rule is instrumental in evolving rectangular shapes. *Rule 17* widens the inside of a U-shape, while *rule 18* widens the outside of an S-shape. For the grammar to be complete some more rules that extend for example the inside of an S-shape and the outside of a U-shape need to be defined.

Fig.9 shows how the final shape generated by the line grammar in fig.5 is evolved by the application of the *extended grammar rules*. The rules update the symbols and labels accordingly and the chain of rectangles emerge as a product of the application of the rules. Fig.10 gives some examples of shapes generated by the shape grammar. The grammar therefore has the capability of generating microstrip shapes and decomposing these shapes into a chain or rectangles, ready for analysis.

5.2 The feedback mechanism

An antenna design can be considered valid if it satisfies the electrical specifications and fits in the designated physical design space. The grammar described in section 5.1 generates the shape of the radiating patch and includes the probe feed. This however does not guarantee that the antenna electrical characteristics are close to the required ones. To generate valid shapes the grammar requires immediate feedback on the values of the electrical properties, throughout the generation process. Needless to say, the model used to compute the approximate values should be very fast to compute.

An antenna is usually characterized by the frequency of operation, input impedance, efficiency, radiation pattern and bandwidth. During the initial phase compact microstrip antenna designers concentrate mainly on the frequency of operation and input impedance. The other electrical properties are either ignored or taken into consideration at a higher level,

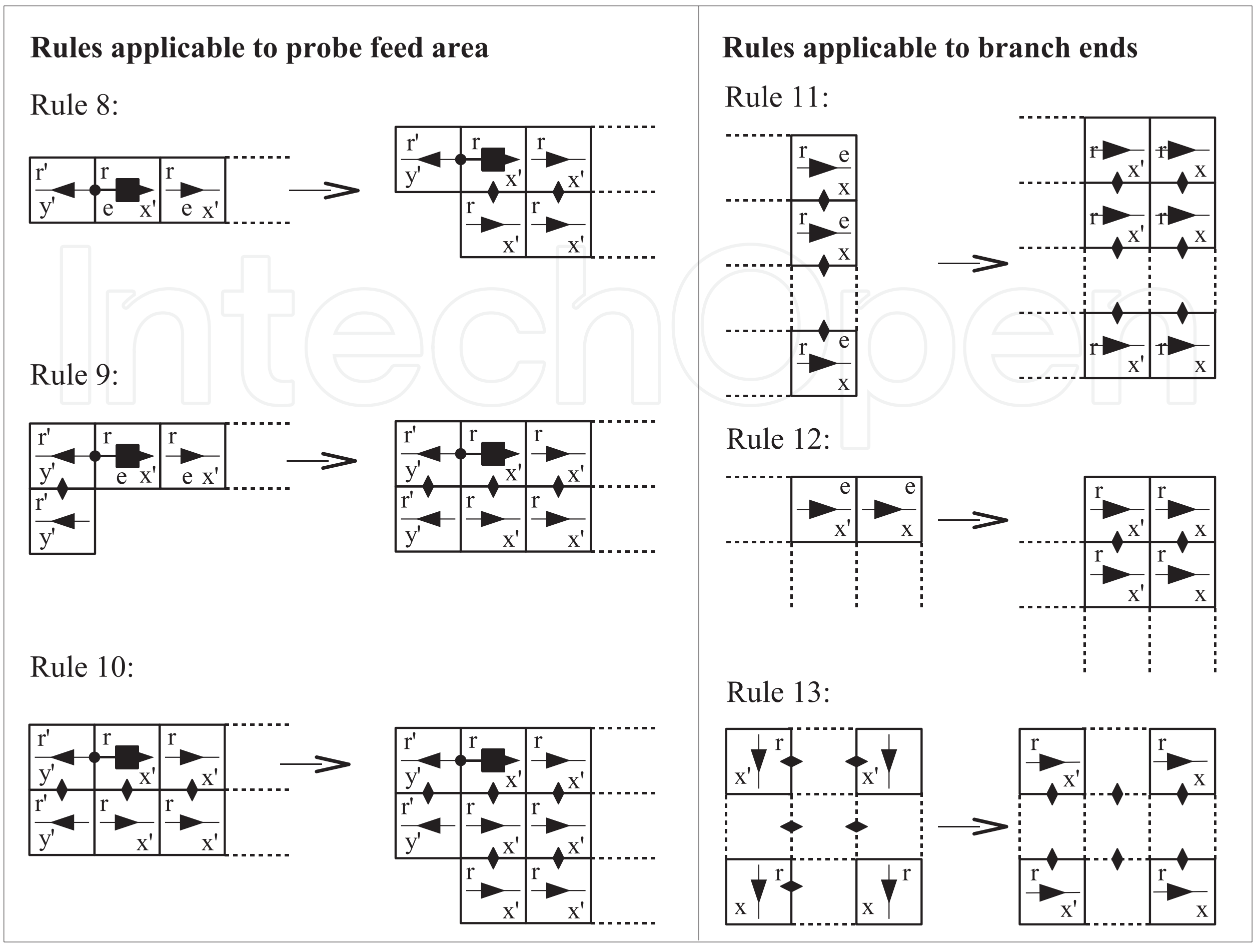


Fig. 7. Extended grammar rules applicable to probe feed area and branch ends.

(Brian S. Collins,2007). For example, it is practically a certainty that the radiation pattern of a compact antenna is essentially an omni-directional pattern with relatively high cross-polar levels and the designer has very little control over this. Efficiency depends on the materials used and bandwidth is taken care of during the selection of topologies and design guidlines which are taken into consideration when selecting the grammar rules and the sequence in which these are applied. Additionally it is common practice to add a final matching circuit to the antenna port once the antenna design is finalized, (Kingsley,S.P.et al.,2008). The frequency of operation and the input impedance are therefore the two properties that need to be considered explicitly in the analysis task and this section describes how these are estimated.

The frequency of resonance and the input impedance are a function of the physical composition of the patch antenna, which consists mainly of the ground-plane size, size and topology of the radiating patch, height of the supporting substrate, the relative permittivity of the substrate, shorting posts or planes and capacitive or inductive components that load the main patch. The microstrip cavity supports an infinite number of modes. However compact antennas are usually operated in the fundamental mode, which is the most useful. For a rectangular patch this mode is excited when the length of the patch is approximately half a wavelength long, or quarter of a wavelength for shorted patches. The rectangular patch can be considered as a wide open-ended transmission line and a standing wave analysis of the $\lambda/2$ line yields good estimates of the fundamental mode frequency as well as the impedance along the line. The width of the rectangular patch determines the impedance bandwidth and the

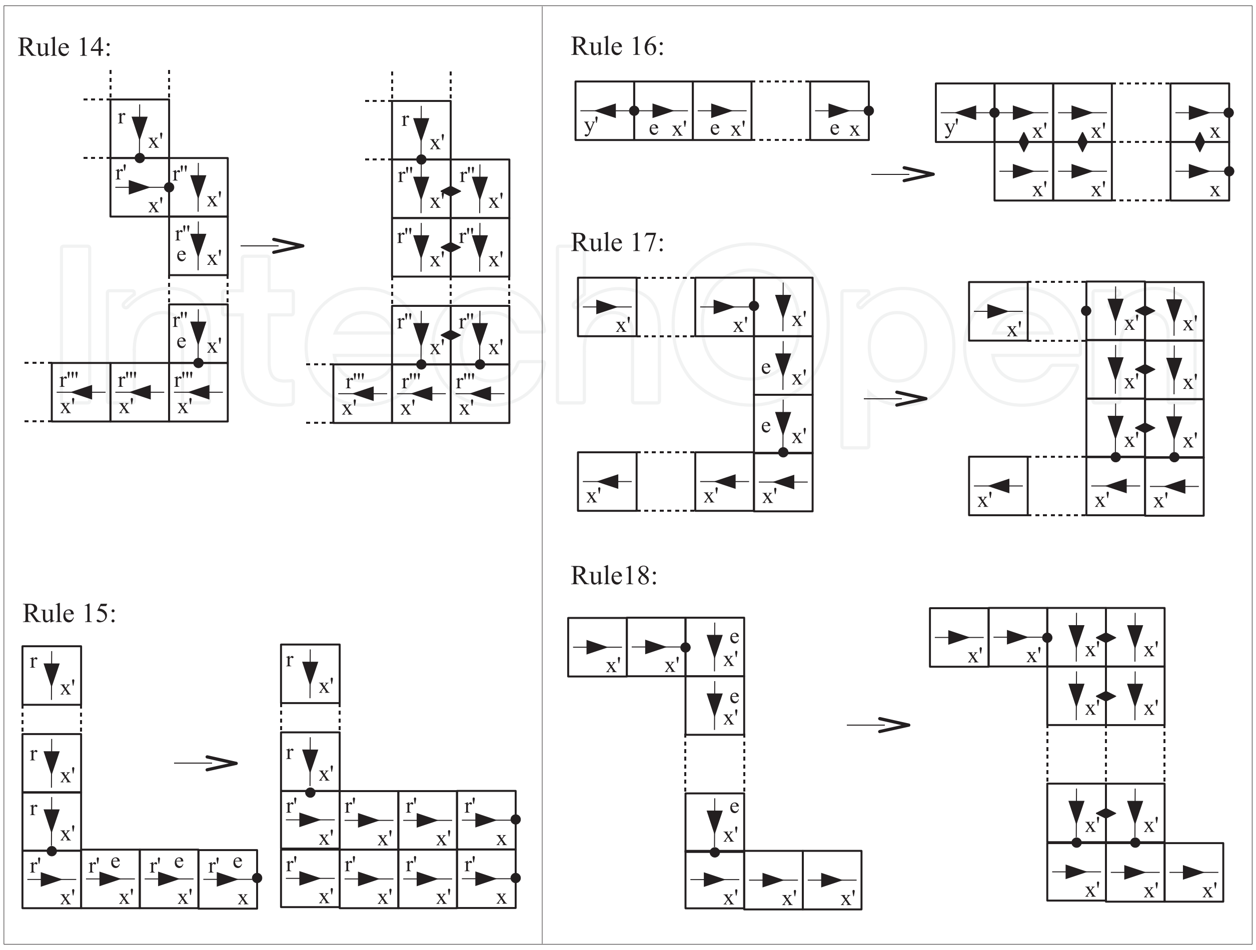


Fig. 8. Extended grammar rules applicable along a branch in between and excluding the start and branch ends.

height of the substrate has an effect on the inductive part of the input impedance. Furthermore the substrate height extends the fringing fields and therefore has a small effect on the value of the resonant frequency.

During the first phase of design the transmission line model and the *design guidelines* are used extensively by compact antenna designers to explore and evaluate a number of shape topologies. During such work high accuracy is not important and the designer uses a combination of qualitative modeling and a crude form of the transmission line model to relate the shape of the radiating patch to the electrical properties. The designer iterates through this process until he is satisfied with the prototype. This iterative process is modelled in the shape grammar with feedback, which can therefore be thought of as a formalization of the design process itself.

The main task for the feedback algorithm is therefore to extract important *geometrical attributes and dimensions*, that are used as inputs to the transmission line model. The resonant frequency and the input impedance depend mostly on the effective current path length and the relative position of the probe feed along this path. Fig.11 is used to explain the process of calculating the effective path length. The first task, which is carried out by the grammar rules during the shape evolution process, is to decompose the shape into rectangles and trace the current paths. The radiating edges are labeled as *a* and *b* and the rectangle interfaces by the *dot* label. The current path direction is labeled by the *arrow* label and the transverse direction by the

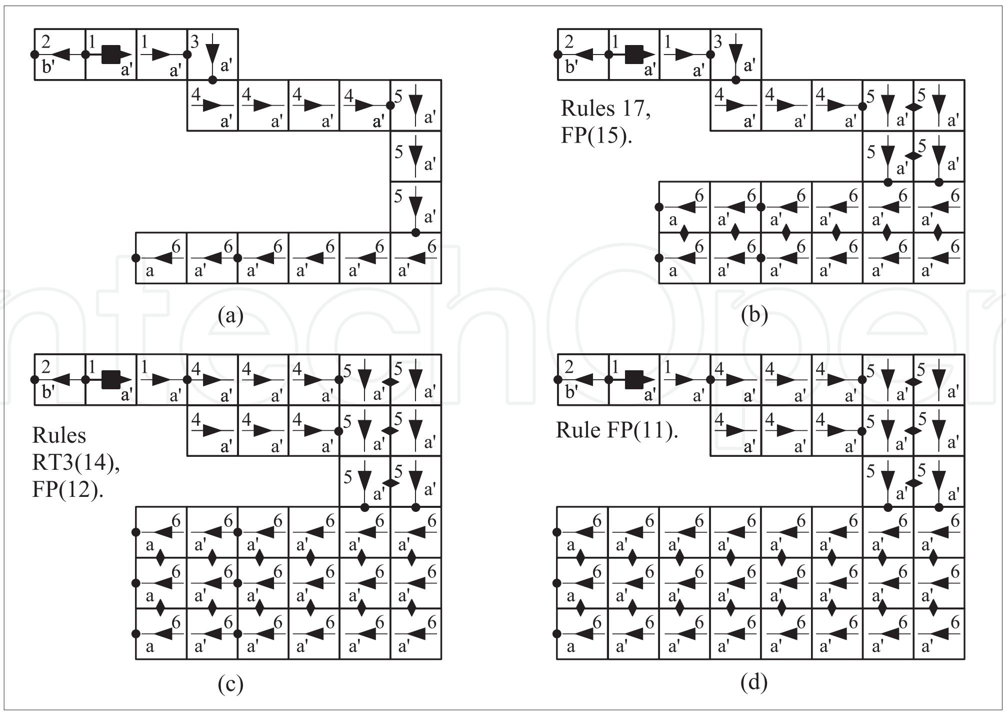


Fig. 9. The evolution of the final shape in fig.5 by the application of the extended rules.

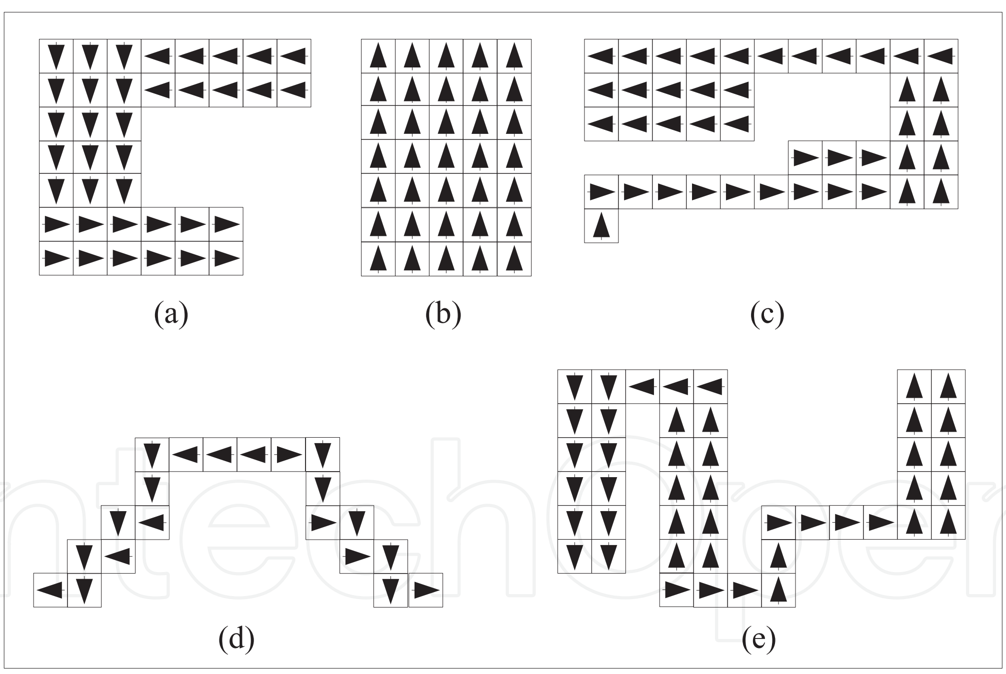


Fig. 10. Examples of shapes generated by the shape grammar.

diamond label. The midpoints of the rectangle interfaces are marked and linked together with straight lines starting from the probe feed. The length of these lines are labeled as L_a for branch *a* and L_b for branch *b*. The number of corners (when the path direction changes) are counted for each branch and labeled as NC_a and NC_b. The L_a, L_b, NC_a and NC_b variables are used to obtain an approximation for the resonant frequency and the input impedance.

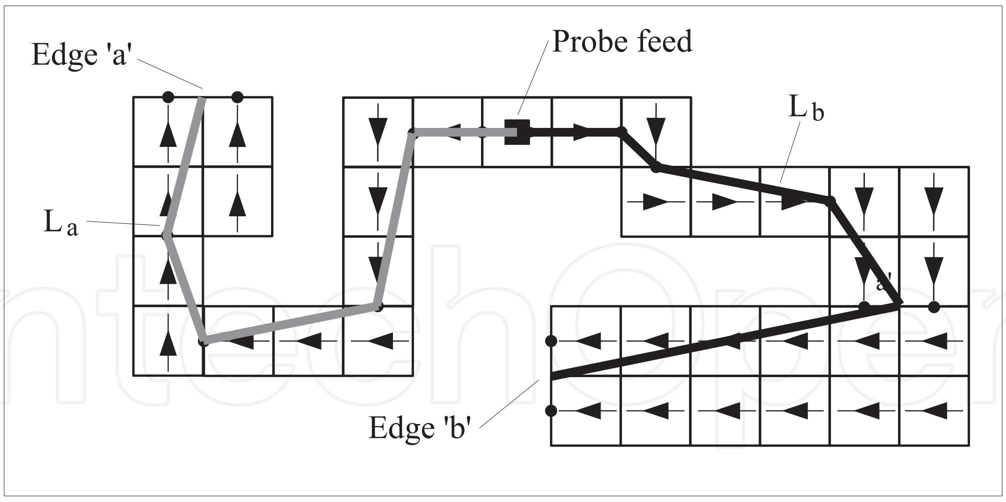


Fig. 11. Evaluation of the effective length.

Intuitively the resonant frequency, f_0 is dependent mostly on L_a, L_b and to a lesser extent on NC_a and NC_b. This intuition is confirmed using scatter plots in (Adrian Muscat,2010). The relationship based on the simple transmission line model for f_0, the frequency of resonance, is derived in (Adrian Muscat,2010) and repeated here,

$$f_0 = 3 \times 10^4 / ((L_a + L_b + (2a_0 - (NC_a + NC_b) * a_1) * L_p) * 2) \quad (1)$$

where, L_p is the width of the square pixel in millimeters. The coefficient a_0 accounts for the field edge extension effect and generally depends on the substrate height and relative permittivity. The coefficient a_1 weights the number of corners. The values for these coefficients are obtained by minimizing the error for a set of prototypes, that is representative of the range of configurations that can be generated.

The input impedance is mainly a function of its position along the length of the patch and on the width of the patch. Compact antennas are characterized by relatively narrow widths and so the width parameter is ignored in the shape grammar model. The input impedance is estimated on the position of the feed only. Furthermore the model does not give a numerical value, but gives a qualitative indication of how far away it is from the system impedance, assumed to be 50Ω. The ratio of the effective length for branch *a* to that of branch *b* is used to judge on this deviation from the system impedance. Experiments reported in (Adrian Muscat,2010) show that when the ratio is in between 0.75 and 0.90 the input impedance is within range of 50Ω. When the ratio is greater than 0.90 the input impedance is significantly smaller than the system impedance and when it is smaller than 0.75 the input impedance is significantly larger.

The coefficients, a_0 and a_1, in eqn.1 are fitted over a set of fifty prototypes that operate over a frequency range of $1.0 - 5.0GHz$. These prototypes are generated randomly and the shapes cover rectangular, L, C and U-shapes, as well as meander lines. The designs are accurately analyzed with a Finite-Difference-Time-Domain (FDTD) model, (Adrian Muscat,2002), and the FDTD results used to tune the coefficients. The average error in estimating the resonant frequency is in the region of 5% with a standard deviation of 3. The errors are smaller for the shapes characterized by narrow rectangles and greatest for the lines characterized by wider rectangles. However for the conceptual or first phase design the accuracy of the model is adequate. Nevertheless, the error can be reduced by fitting the model over a smaller frequency range and a more specific topology. In the next two sections examples are used to demonstrate the use of the shape grammar with feedback.

5.3 Example in multi-band design

In this section the shape grammar is deployed in the conceptual design of a mobile terminal antenna consisting of a single feed dual-band antenna operating at 0.925GHz and 1.8GHz and a separately fed antenna for 2.45GHz. These frequencies correspond to cellular licensed mobile communications bands and the unlicensed Industry, Scientific and Medical (ISM) band. The prototype is projected on a rectangular design space. The single feed cellular antenna consists of two combined shorted patch elements. The two patch elements are first evolved separately and then joined together at a later stage. The *line grammar rules* are applied to evolve one-pixel wide elements as well as to explore the design space. Most of the designs evolved at this stage are discarded and some are stored as candidates to be further evolved by the *extended grammar rules* that widen the rectangles, which make up the initial shape, starting from the one at the end of the line. During the second stage the process is allowed to remove any one of the other elements to make space for the current element. This however necessitates the re-application of the *line grammar rules*. An extracted sequence of interim designs during the evolution of the antenna is shown in fig.12. The initial shape generated with the *line grammar rules* is shown in fig.12(a), where the *rules* are applied simultaneously to the three elements. The *extended grammar rules* are then applied to the 1.8GHz element on the left-hand-side and extends the last rectangle. This results in a shape that does not satisfy the specifications and there is no more space to correct the error, fig.12(b). Therefore the conflicting element is removed and the first element is allowed to evolve. The *line grammar rules* are applied again which in turn conflict with the third element and these two elements are re-designed simultaneously, fig.12(c). The *extended grammar rules* are then applied to the central element starting from the rectangle at the end of the line with no success,fig.12(d). So the third element is removed and the rectangle is widened. The *line grammar rules* are then applied to the third element and the initial design is complete, fig.12(e).

The estimated frequencies of resonance are 1.86GHz, 1.05GHz, and 2.47GHz, and the respective deviations from the target values are 3.5%, 13.2% and 2.1%. The 1.8GHz and the 0.925GHz elements are combined to create a single feed dual-band structure and shorting planes are added to the dual-band patch as well as to the ISM patch. The structure shown in fig.12(f), is analyzed with an FDTD model. The three bands resonate at 0.85GHz, 1.69GHz, and 2.52GHz and the deviations from the grammar model are 18%, 9% and 2%. The smaller resonant frequencies are due to the increase in length when the two elements are combined as well as due to the shorting plane which is narrow than the line width. Additionally both feeds are sufficiently closely matched to the system impedance.

At this point in time the antenna designer proceeds to the second phase - the detailed design, where the structure is optimized using a numerical model. Fig.12(f) indicates some variables for optimization. It should be noted that the optimization process will not change the topology of the shape itself, but only the dimensions of the sub-shapes or rectangles.

5.4 Example in the control of a reconfigurable antenna

The pixel reconfigurable structure described in section 2 requires algorithms that search in real-time for configurations that yield the required electrical specifications. The transient performance of such algorithms is therefore important. In this example the shape grammar is used as part of a control algorithm that can efficiently tune the reconfigurable pixel microstrip

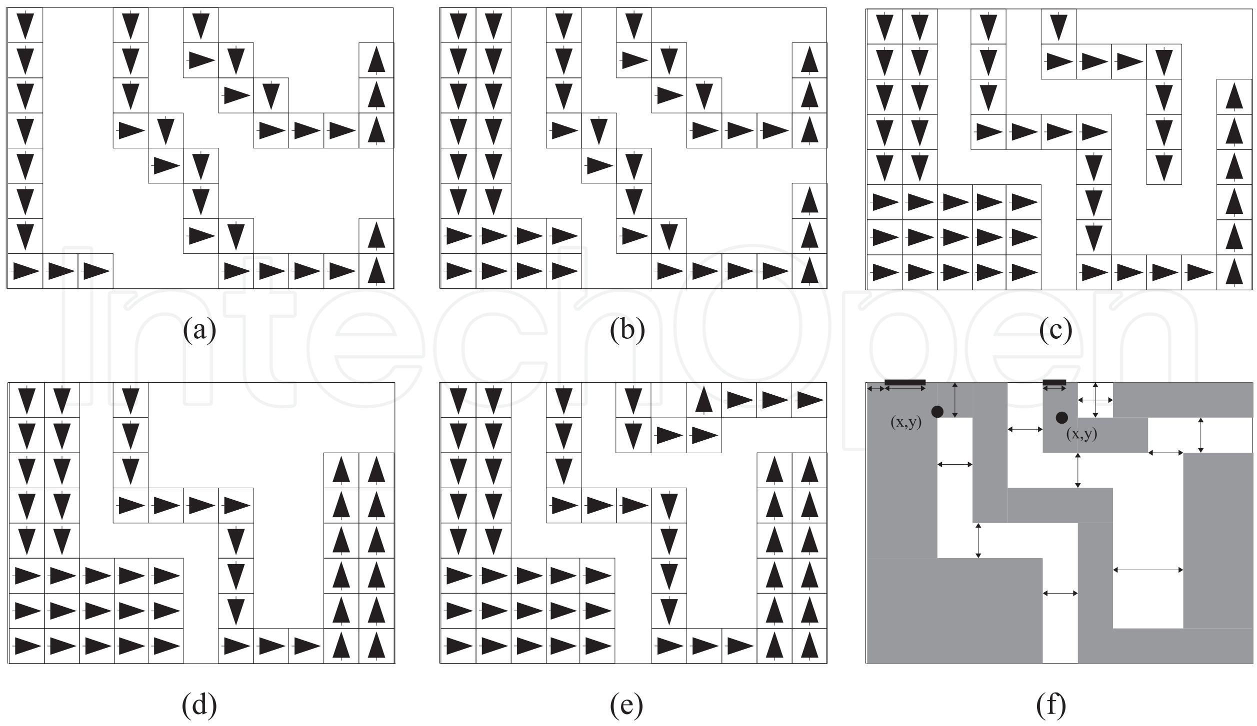


Fig. 12. (a) to (e) stages during the design process of a tri-band separately fed structure, and (f) the numerical model ready for optimisation. The arrows and positions for the probe feeds are suggested variables for the optimisation process.

antenna 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.

A system diagram for the algorithm is shown in fig.13. The search algorithm instructs the *shape grammar model* to suggest a valid shape that is likely to satisfy the specifications received from the transceiver. The search algorithm accepts or rejects the suggestion, depending on whether the estimated electrical characteristics fall within a specified range. If accepted the shape is hardware switched and measured feedback is used to terminate or proceed with the search. This process continues until an acceptable solution is found. The measurements can also be used to tune the model coefficients. This algorithm works on the premise that the *designs* exhibit characteristics that are close to the intended targets. As used here the shape grammar model reduces a global search problem to a local random search. Furthermore for this application the shape grammar details needs to be modified since the shape is synthesized by switching the interconnections rather than the pixel itself. The modifications are described in detail in (Adrian Muscat et al.,2010).

The control algorithm is demonstrated on two cases (a) $\lambda/2$ patch shape operating at $1.8GHz$, and (b) $\lambda/4$ shorted patch shape operating at $0.9GHz$. For these two examples, the candidate shapes are generated with the algorithms given in fig.14 and fig.15. *Algorithm A* generates the one-pixel wide shape, while *Algorithm B* evolves the rectangles that make up the initial shape. For case (a) 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 substrate height is $3.0mm$ and its relative permittivity $\varepsilon_r = 1.0$. In this example the coefficients are tweaked to $a_0 = 0.6$ and $a_1 = -0.1$. The candidates are then simulated with the FDTD model, which is used as a

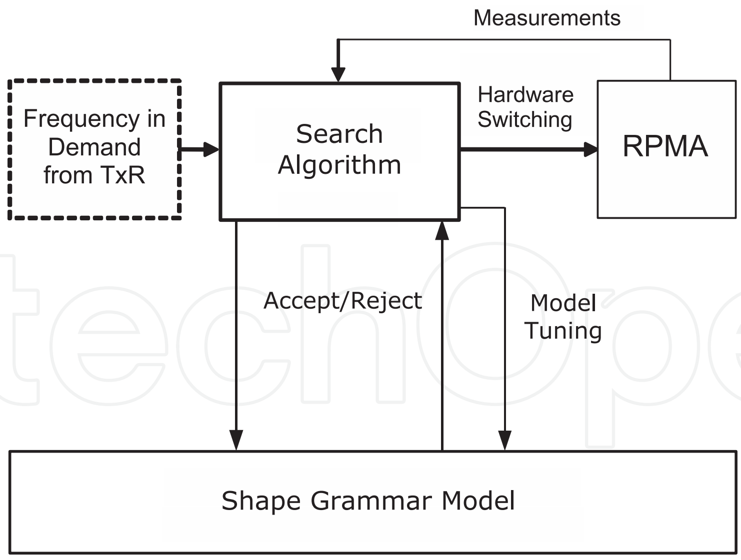


Fig. 13. Block diagram for the control algorithm based on a random search method and a shape grammar model, modified from (Adrian Muscat et al.,2010).

benchmark and replaces measurements. Table 1 list the first 30 candidates in the run. The best candidate is off the frequency mark by 0.556% and for this case occurs at the 25^{th} iteration. The error for the second best candidate is 0.833% and occurs at the 14th iteration. The topologies for these two candidates are shown in fig.16.

In case (b) the antenna is a 10×16 pixel structure and the total size of the square antenna patch is $26mm \times 41mm$ with a pixel size of $2.05mm \times 2.05mm$. The substrate height is $3.0mm$ and its relative permittivity $\varepsilon_r = 1.0$. The candidate shapes are generated with algorithms A and B and in this case a shorting post is added. Equation 1 is therefore adjusted to,

$$f_0 = 300/4(L_e + (2a_0 + a_1 NC)L_p) \tag{2}$$

Table 1 lists the first 30 candidates in the run. The error for best candidate is 0.889% and occurs at the 19^{th} iteration. The second best candidate is off the frequency mark by 1.778% and occurs at the 28^{th} iteration.These two designs are shown in fig.17.

The above cases show that within $20 - 30$ iterations a solution is usually found and demonstrate how effective a grammar based qualitative model can be in reducing the number of switching iterations required. This result is a major gain over systems that rely solely on a GA.

6. Conclusions and future work

This chapter described a shape grammar that generates compact microstrip antenna patch shapes in a constrained 2D space. A feedback loop based on an approximate transmission-line model is used during the shape generation process such that the shapes suggested are valid and closely satisfy the specifications in hand.

The shape grammar with feedback tool formalizes and mimics the informal and intuitively based *cut and try* process that compact microstrip antenna designers follow. The shape grammar generates shapes, decomposes these shapes into a chain of rectangles and positions the feed to match the structure to the system impedance. Labels are used to derive the topology of the shape and to extract shape attributes and parameters that are

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;

Fig. 14. Algorithm Synthesize A: Generates meander-line elements whose width is equal to one pixel, from (Adrian Muscat et al.,2010)

utilized estimating the frequency of resonance and the input impedance. These electrical characteristics are exploited to guide the selection of rules and therefore influence the shape evolution process.

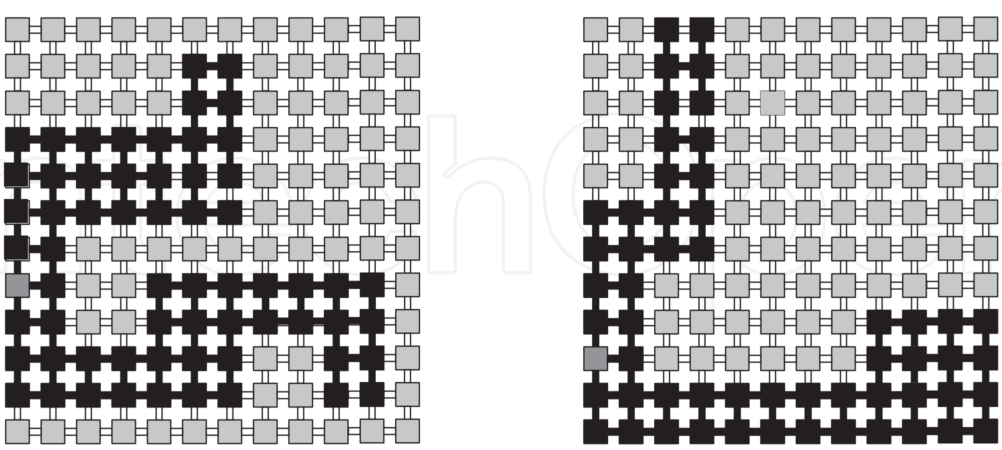
When deployed as a tool in design, the shape grammar can generate a wide variety of potentially useful structures and can form the basis of an Intelligent Computer Aided Engineering (ICAE) software, that acts as a junior partner as described by (Kenneth D. Forbus, 1988). Such a tool can therefore reduce costly design time and can also be used to capture and re-use antenna design knowledge. This concept is demonstrated in the synthesis of a multi-band compact antenna.

The shape grammar is also illustrated in the real-time control of reconfigurable antennas, where a fast and efficient control algorithm is desired. A random search algorithm considers a candidate solution by the grammar and based on measured results accepts or rejects the candidate. This process continues till an acceptable solution is found. Due to the relatively good accuracy of the model, the algorithm converges much faster than a Genetic Algorithm.

The approximate transmission line model performs very well for narrow element designs and when fitted over a narrow range of shapes and frequencies. However the accuracy degrades as more variables are introduced. Nevertheless, the accuracy of the model is still good enough for its intended purpose, the initial design phase. On the other hand it is always desired to have a single model applicable to a wide range of topologies and frequencies. Neural Network architectures (NN) have been proposed as a replacement to the CAD formula for microwave devices, (K. C. Gupta,1998), where physical attributes are assumed as inputs to the NN which in turn yields the frequency of operation or wide-band input impedance. This approach has been shown to work for microstrip antennas of standard shapes,(Kerim Guney et al.,2002) and

```
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
   {
07 For Each rectangle along a branch (starting from the
   end) do
   {
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;
   }
   }
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
```

Fig. 15. Algorithm Synthesize B: Generates meander-line elements whose width is greater than one pixel, from (Adrian Muscat et al.,2010)



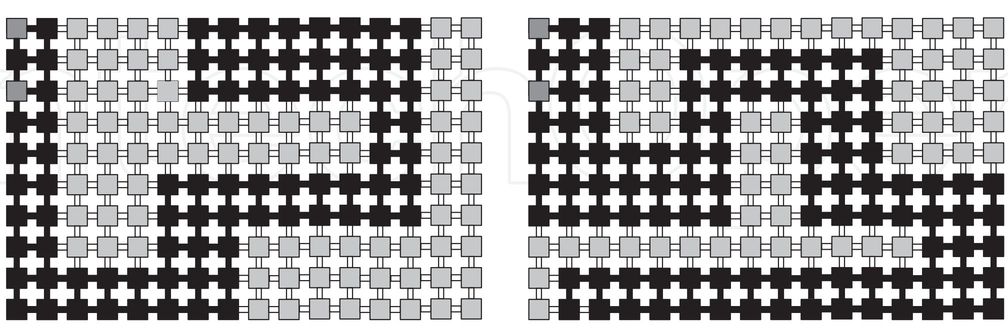
(a) (b)

Fig. 16. The best two candidates resonating at 1.8GHz, from (Adrian Muscat et al.,2010)

(Heriberto Jose Delgado et al.,1998). It is therefore of interest to research on whether NNs can improve the accuracy of the shape grammar in analysis.

Table 1. Candidates for the 1.8GHz set and the 0.9GHz set, from (Adrian Muscat et al.,2010).

		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)

Fig. 17. The best two candidates resonating at 0.9GHz, from (Adrian Muscat et al.,2010)

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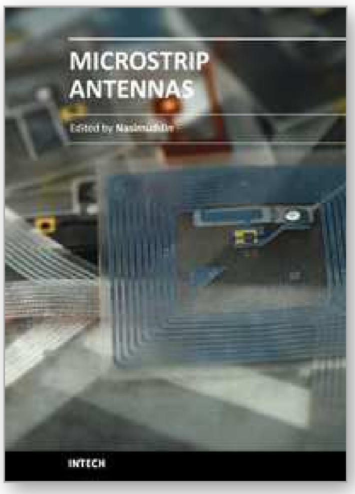

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In the last 40 years, the microstrip antenna has been developed for many communication systems such as radars, sensors, wireless, satellite, broadcasting, ultra-wideband, radio frequency identifications (RFIDs), reader devices etc. The progress in modern wireless communication systems has dramatically increased the demand for microstrip antennas. In this book some recent advances in microstrip antennas are presented.