Appendix: Fuzzy Logic based Energy and Throughput aware Design Space Exploration for MPSoCs

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Appendix A. Introduction to Fuzzy Logic

Fuzzy logic uses a collection of membership functions defining input and output variables and specifies their corresponding relationship by IF-THEN based conditional statements called rules.

Appendix A.1. Membership Functions

In contrast to a crisp-set, in which an element can belong to a set or not (i.e. having membership value of 1 or 0), a fuzzy logic membership function is a curve that defines the mapping of input values to a membership value between 0 and 1 [34]. This, in turn makes it convenient to represent linguistic labels such as slow, fast, medium, heavy etc. Although there are many types of fuzzy membership functions such as pi, bell, trapezoidal etc, we only describe in REFER Table A1, rectangular or discrete, and triangular functions as they are used in this article.

Appendix A.2. Logical Operations

In fuzzy logic, logical operations such as AND, OR, NOT have corresponding equivalents such as min, max, and complement and are defined as following [35]

$$\mu_{(A\cup B)}(x) = max[\mu_A(x), \mu_B(x)]$$
$$\mu_{(A\cap B)}(x) = min[\mu_A(x), \mu_B(x)]$$
$$\mu_A(x) = 1 - \mu_A(x)$$

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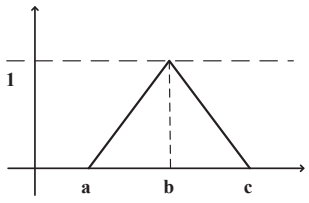
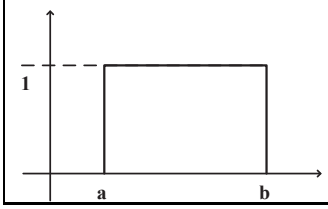
Table A.1: Triangular and Rectangular Membership Functions

Membership Function	Definition
	$\mu_{x;a,b,c}= \begin{cases} 0 & for\ x < a \\ \frac{x-a}{b-a} & for\ a \leq \text{ x } < b \\ \frac{c-x}{c-b} & for\ b \leq \text{ x } \leq \text{ c} \\ 0 & for\ x > c \end{cases}$
	$\mu_{x;a,b}= \begin{cases} 0 & for\ x < a \text{ or } x > b \\ 1 & for\ a \leq \text{ x } \leq \text{ b} \end{cases}$

Appendix A.3. If-Then Rules

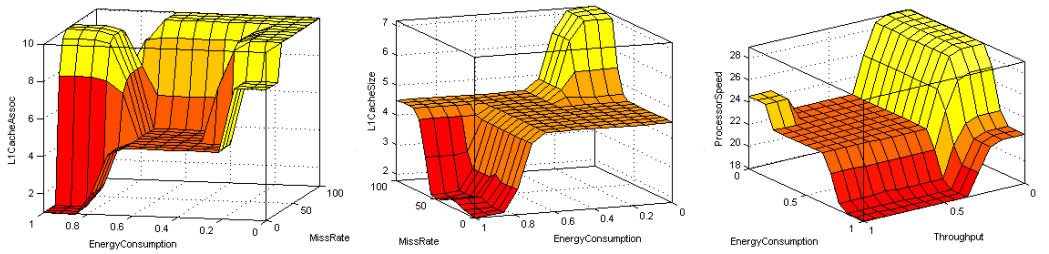
The fuzzy logic rules comprise of if-then statements operating on the fuzzy sets using fuzzy operators e.g. If temperature is high then put the fan at high speed If temperature is very low and humidity is high then put the heater at high temperature. Generally, a single rule cannot specify the relationship among the inputs and outputs so two or more rules are required. The output of each rule is a fuzzy set, which are aggregated to find a single output fuzzy set. The resulting fuzzy set is then defuzzified to get a crisp number output which could be applied to the physical world.

Appendix A.4. Fuzzy Inference Systems

The process of formulating the mapping from input to output using fuzzy logic is the fuction of fuzzy inference systems. This article has used Mamdanis fuzzy inference system [25] which was among the earliest implementations of fuzzy logic in a control system. For defuzzification centeroid of the curve method was used to find the crisp output.

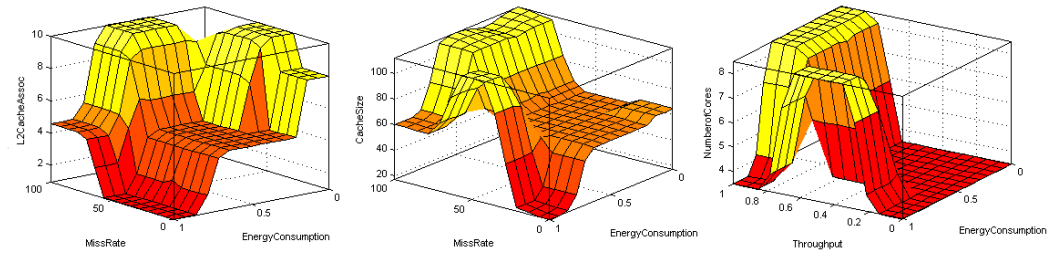
Appendix B. Fuzzy Logic Rules

The fuzzy logic system provides a mean to form a rule base in linguistic terms. There is no set criteria to form a rule base therefore the overall



(a) (b) (c)

Figure B.1: Core level Rules: (a) L1 Cache Associativity and Energy Consumption vs. L1 Miss ratio, (b) L1 Cache Size and Energy Consumption vs. L1 Miss ratio, and (c) CPU frequency and Energy Consumption vs. Throughput



(a) (b) (c)

Figure B.2: System or SoC level Rules: (a) L2 Cache Associativity and Energy Consumption vs. L2 Miss ratio, (b) L2 Cache Size and Energy Consumption vs. L2 Miss ratio, and (c) Number of CPU cores and Energy Consumption vs. Throughput

performance of the system relies on the quality of rules. However the robustness of fuzzy systems does not allow the response to degrade intermittently as the quality of knowledge base degrades [48]. A set of rules is defined for E-FLORE relating input and output variables, and are detailed in Table B.2, B.3. For further explanation, an example can be taken of the first rule in Table B.2, i.e.

if "L1 Miss ratio" ***is*** LOW ***and*** "Energy Consumption" ***is*** LOW ***and*** "Throughput" ***is*** LOW ***then*** "L1 Cacahe Associativity" ***is*** NO CHANGE, "L1 Size" ***is*** NO CHANGE ***and*** "Clock Frequency" ***is*** HIGH

The impact of these rules and resulting interdependance of system parametrs and output variables can be observed in Figure B.1, B.2.

Table B.2: Core level Rules for E-FLORE

L1 Miss ratio	**Energy Cons.**	**Throughput**	**L1 Cache Assoc.**	**L1 Size**	**Clock Freq.**
L	L	L	-	-	H
L	L	M	-	-	M
L	L	H	-	-	-
L	M	L	M	M	H
L	M	M	M	M	M
L	M	H	M	M	M
L	H	L	L	L	M
L	H	M	L	L	L
L	H	H	L	L	L
M	L	L	H	M	H
M	L	M	H	M	M
M	L	H	H	M	-
M	M	L	M	M	H
M	M	M	M	M	M
M	M	H	M	M	M
M	H	L	H	L	M
M	H	M	H	L	L
M	H	H	H	L	L
H	L	L	H	H	H
H	L	M	H	H	M
H	L	H	H	H	-
H	M	L	H	M	H
H	M	M	H	M	M
H	M	H	H	M	M
H	H	L	M	M	M
H	H	M	M	M	L
H	H	H	M	M	L

Table B.3: SoC level Rules for E-FLORE

L2 Miss ratio	**Energy Cons.**	**Throughput**	**L2 Cache Assoc.**	**L2 Size**	**No. of Cores**
L	L	L	-	-	L
L	L	M	-	-	L
L	L	H	-	-	M
L	M	L	M	M	L
L	M	M	M	M	L
L	M	H	M	M	M
L	H	L	L	L	L
L	H	M	L	L	M
L	H	H	L	L	L
M	L	L	H	M	L
M	L	M	H	M	L
M	L	H	H	M	M
M	M	L	M	M	L
M	M	M	M	M	L
M	M	H	M	M	M
M	H	L	L	H	L
M	H	M	L	H	M
M	H	H	L	H	L
H	L	L	M	H	L
H	L	M	M	H	L
H	L	H	M	H	M
H	M	L	H	H	L
H	M	M	H	H	L
H	M	H	H	H	M
H	H	L	M	M	L
H	H	M	M	M	M
H	H	H	M	M	L