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Perceptual Computing Based Performance Control Mechanism for Power Efficiency in Mobile Embedded Systems

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***Abstract*-A computing with words/Per-C based user feedback collection model for controlling the processor power efficiency is introduced. Needless to say that CWW/Per-C is a very efficient tool in modelling human perceptions. Here the objects of computation are the words drawn from natural language instead of numbers [22],[23]. Perceptions alone don't make the sole criteria rather the backed logic of reasoning is also a supportive tool in the same scenario. In our present work, we have proposed a new algorithm viz. UFOPeC (user feedback optimized perceptual computing) for obtaining the optimal power efficiency in adaptive computing systems that can run at multiple operating voltages. Our approach models the user satisfaction very well and more realistically as compared to than the other existing mechanisms like HAPPE [1] as we have taken the user feedback in terms of words and modelled the same using the IT2 FSs (interval type-2 fuzzy sets). An appropriate numerical example has been chosen to demonstrate the design of our model.**

Keyword: Fuzzy sets, type-1 FS, type-2 FS, IT2 FSs, Computing with words (CWW), variable voltage processors, frequency scaling, processor power efficiency, Dynamic Voltage and Frequency Scaling (DVFS)

I. INTRODUCTION

Power consumption is a serious issue plaguing the battery operated computing nodes today. It has been established through a number of studies that a major component of this power consumption is that of the processor power [31]. Over the time, DVFS technique [16] could establish itself as foremost mechanism for running a computing processor with reduced power. DVFS based processors can run on multiple voltage levels allowing a significant avenue for power optimized execution of particular computing application. It is noted here that energy consumption in current DVFS based systems is proportional to the processor frequency and square of supply voltage. On the contrary a processor frequency is directly proportional to the supply voltage. So, in the nutshell, scaling down the processor frequency can greatly decrease the power consumption. However, this may bring dissatisfactions amongst the users since reduced frequency will affect perceived system performance up to certain extent as various users may have diverse satisfaction requirements from the same systems for a specific application. This justifies that efforts are also needed to consider the satisfaction of the users while deciding on the appropriate frequency/voltage levels for reduction of power consumption by a computing machine while running an application. None of the processor power saving techniques including DVFS could offer the flexibility for the incorporation of the “user satisfaction” as one of the criteria for deciding on the appropriate frequency/voltage at which the processor should run.

An interesting computational model for satisfying the users by taking their feedback from two additional keys on the keyboard, “performance” key and “power” key has been proposed by L.Yang et. al. in [1]. This model was termed as HAPPE, which stands for Human and Application-Driven Frequency Scaling for Processor Power Efficiency. According to HAPPE, if a user is not satisfied with the current system frequency, the user is required to press the "performance" key to step up the frequency by one level and "power" key to step down the system frequency to save the power if the user is satisfied with the current system frequency but wants to save the system power. But a major drawback of the approach is that user is constrained to express his or her choice by pressing only two keys on the keyboard which is definitely not the most natural way of expressing the views of the users. Humans naturally express in terms of ‘words’. Therefore the CWW is exploited for modelling the users’ feedback. CWW, first introduced by professor L. A. Zadeh [10],[11],[6], is inspired by the human capability of performing a variety of tasks without any measurements and computations. Underlying this is the crucial ability of humans to manipulate perceptions. A striking feature of the two is that measurements are in general crisp whereas perceptions are fuzzy. Methodology of CWW maps the linguistic expressions into numbers to be used for computation by any machine and facilitates in making subjective judgements in uncertain environments. Another area that is commonly used in association with CWW is the perceptual computing. Perceptual computing has a component called the perceptual computer (Per-C) that manipulates the perceptions. The output of Per-C is the data that can be put to use in effective decision making. Per-C finds applications at number of places such as investment judgement, social decision making, etc.

In the present work, we have developed a perceptual computing based performance control mechanism for power efficiency in mobile computing systems. We have shown that our model works better in taking the users’ feedbacks, thus making the system more adaptive as well as power efficient in satisfying a wide variety of users’ demands. A real-life example is given to demonstrate the effectiveness of our model. The rest of the paper is organized as follows: Section 2 gives a brief explanation on the mathematical preliminaries; in Section 3 we give the details of perceptual computing. In Section 4 we give the model for the Per-C processor frequency advisor. Finally the paper concludes with a summary in Section 5.

II. MATHEMATICAL PRELIMINARIES

We shall now give some basics of the fuzzy set theory on which our problem formulation relies. At first we discuss the distinction between crisp sets and fuzzy sets. Then we give methodology to construct T2 FSs from the T1 FSs.

A. Type-1 Fuzzy sets: a brief review[2]

A fuzzy set $\breve{\boldsymbol{A}}$ consists of a collection of objects along with their membership values. It is denoted by $\breve{A}= \{(x, \mu_{\breve{A}}(x))| x\epsilon X\}$. Here $\mu_{\breve{A}}(x)$ is called the membership function or grade of membership of x in $\breve{A}$. This membership function gives the idea of level of containment of x in $\breve{A}$. If the highest grade of membership function value is 1 then the fuzzy set is called normal. Any non empty fuzzy set can be converted to normal by dividing all the membership values by the highest membership value. Most commonly, there is also the case that T1 FS may depend on more than one variable. Consider the case that the MF is bi-variate. So, the plot of the FS MF will be three dimensional. However if it is possible to assign a value to a variable as the words drawn from the natural language, then the variable is said to be the linguistic variable. A linguistic variable can be described fully by a quintuple (v, T, X, g, m) where

V: name of variable

T: set of linguistic terms for v whose values range over the universal set X

g: syntactic rule for generating linguistic terms

m: semantic rule that assigns to each linguistic tϵT its meaning m(t) which is a fuzzy set on X.

B. Type-2 Fuzzy sets[5]

The grades of memberships in a type-1 fuzzy set are crisp whereas in type-2 FS are fuzzy and that is why they are also called fuzzy fuzzy-set. As shown in the Fig. 1 below, type-1 FS have crisp grade of membership whereas the IT-2 FS[12] have fuzzy grade of membership which is shown in Fig.2.

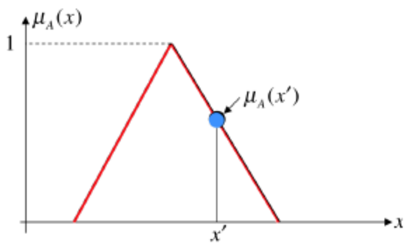

Fig 1: Membership grades for T1 FSs (crisp)[17]

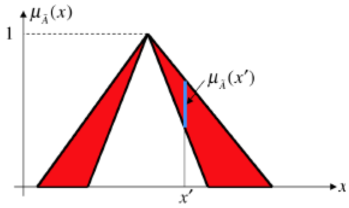

Fig 2: Membership grades for T2 FSs (fuzzy)[19]

Need for IT-2 FS arises because as shown in the figure for T1 FS, it does not take into account the uncertainity about the two end points that rest on the x-axis. It is taken by the type-2 FSs. The shaded region shown in the above figure is called the footprint of uncertainty (FOU). IT-2 FSs rest on the top of the footprint of uncertainty (FOU). If all the randomness of type-2 FSs vanishes, then they are reduced to type-1 FSs as shown by the dashed triangle in the Fig. 3 below with end points on the axis as l and r respectively. Here l and r are the average of the left end point and right end point values respectively associated with the data under observation. If we drop a perpendicular onto the x axis at a point say x' such that the perpendicular cuts the FOU at points u1 and u2. If we then take the u1 and u2 onto the horizontal axis, then we obtain a plot similar in Fig.4.

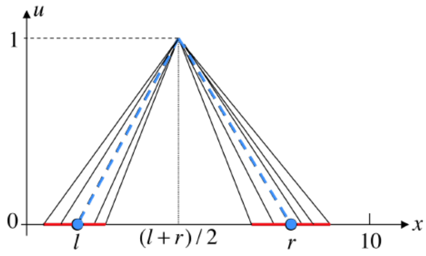

Fig 3: Footprint of uncertainty of fuzzy sets[19]

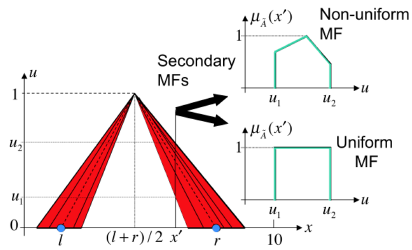

Fig 4: Primary and secondary grades of memberships of IT2 FSs[19]

This is called the secondary membership function. There are generally two types of type-2 FSs: general T2 FS and interval T2 FS based on the fact that that secondary MF is non uniform and uniform respectively. For each associated FOU, we have an upper membership function (UMF) and lower membership function (LMF) respectively as shown in Fig. 5.

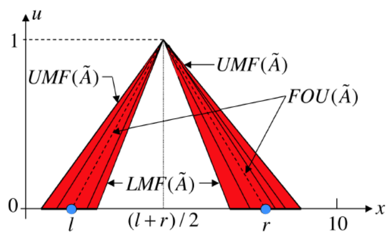

Fig 5: Upper MF and Lower MF of IT2 FS

Similar to T1 FSs, some important set theoretic operations namely, complement, union, intersection, etc. can be performed on T2 FSs too [32]. Some of these operations as well as the determination of the centroid of the T2 FSs are necessary for the defuzzification/ type reduction of the T2 FSs. The well known Karnik-Mendel (KM) algorithms and its further ramifications are very popular and extensively employed for this purpose [33].

III. DETAILS OF THE Per-C

We now discuss the mathematical foundations of the Per-C here briefly. Anyone interested in dwelling in the details may refer [3]. Perceptual computing is an area that branches out of the CWW in which CWW is used for making subjective measurements. Subjective measurement is a personal opinion that has been influenced by ones personal views, experience or background. Examples include investment decision making. The general model for design of Per-C can be found in [3],[7],[8]. According to Mendel, humans make subjective measurements not only using perceptions but also provide reasoning using the data. A perceptual computer or Per-C used by Mendel consists of three components as shown in Fig. 6.

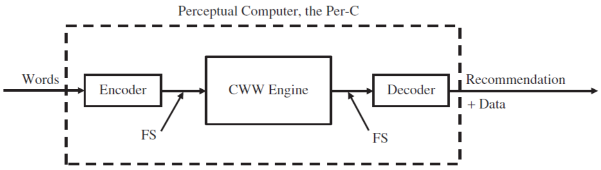

Fig 6: Basic components of a Per-C

1. Encoder: transforms words into FSs and leads to codebook. Codebook is a collection of words along with their associated values grade of membership.

2. CWW engine: converts type-1 FSs to interval type-2 FSs. The input to the CWW engine is the values that represent the end point data for left and right end point. Then plots for FOUs are built on the basis of the IT2 FS values. The output is the corresponding type-2 FS FOU for the word.

3. Decoder: converts interval type-2 FSs back to human understandable words. This component aids in the process of decision making by providing recommendations.

According to Mendel, a project is called CWW if it passes all of the three following tests:

- A word must lead to membership function rather than membership function leading to a word.
- Numbers alone may not activate the CWW engine
- The output from a CWW must be at least a word and not just a number.

The fourth test is optional but is strongly suggested: the words must be modelled using at least type-2 fuzzy sets.

A. The Encoder

First step in the design of Per-C is the design of encoder. The process starts with the building of a vocabulary of application dependent words (W_i) which later, along with their IT2 FS models constitute a codebook for an application i.e. codebook= {(W_i, FOU(W_i)), i=1, ..., N_A}. According to Mendel, uncertainty about a word is of two types: intra and inter uncertainty. Which essentially mean the uncertainty a person has about a word and uncertainty that a group of people have about a word respectively. A FOU uncertainty drawn after collecting data from a group of subjects is called person FOU and it also gives the information about intra as well as inter uncertainty of a word. A person FOU contains within it, first order and second order uncertainties. First order uncertainty is the one that exists about the person FOU and the one that exists about the weights that might be assigned to each element of the person FOU is called the second order uncertainty. However, person FOUs don't have to be smooth and also their upper and lower bounds need not be continuous. However, a constraint that each person must adhere to while sketching their FOU is that upper bounds can't exceed 1 and lower bounds can't be less than 0, the upper and lower bounds can't change direction more than one time and lastly, the FOU can't extend outside the domain of the primary variable. Each person FOU enables the modelling of intra-uncertainty about a word and collection of person FOU enables the modelling of inter-uncertainty about a word. While aggregating these FOU, we can assign equal weights to all person FOU so that it can be easily normalized out of the final description. Even though second case is more realistic but it may lead to further unending levels of uncertainty. So, uniform weighting scheme is preferred. For aggregation, Union is the preferred mathematical operator because it preserves the information about differences as well as commonalities across different person FOU as well as preserves the upper and lower bounds associated with the set of person FOU. Consider that there are n_w subjects/ persons. So, we get the following representations for an IT2 FS for a word:

$$\widetilde{W} = \bigcup_{j=1}^{nw} \widetilde{w}(p_j) = \bigcup_{j=1}^{nw} \int_{x\in X} \mu_{\widetilde{w}}(x|pj)/x$$
$$= \bigcup_{j=1}^{nw} \int_{x\in X} [a_{\widetilde{w}}(x|pj), b_{\widetilde{w}}(x|pj)]/x$$

where $\widetilde{w}(pj)$ is the IT2 FS notation for one person pj $a_{\widetilde{w}}(x|pj) and b_{\widetilde{w}}(x|pj)$ denote lower and upper bounds respectively of the IT2 FS person FOU. In the above equation, the $\int$ indicates union within members of a person FS and $\bigcup$ represents union across person FSs. So, it's possible to distinguish between union of sets and union among members within individual sets. Denoting $\underline{\mu_{\widetilde{w}}}$(x)= min $a_{\widetilde{w}}(x|pj)\forall x \in X$and j=1,2,.....$n_w$ and $\overline{\mu_{\widetilde{w}}}(x)$= max $a_{\widetilde{w}}(x|pj)\forall x \in X$and j=1,2,.....$n_w$ be the LMF and UMF values of $\widetilde{W}$ at any x∈X respectively. This lets us define two additional terms based on this as:

$$\underline{\widetilde{W}} \equiv \mathrm{LMF}(\widetilde{W}) = \int_{x\in X} \underline{\mu_{\widetilde{w}}}(x)/x \text{ and}$$
$$\overline{\widetilde{W}} \equiv \mathrm{UMF}(\widetilde{W}) = \int_{x\in X} \overline{\mu_{\widetilde{w}}}(x)/x.$$

Using the LMF and UMF, a filled in FOU($\widetilde{W}$) is obtained. Then it's desired to obtain a shape of the lower and upper bounds of parametric model of the filled in FOU($\widetilde{W}$). The parameters for drawing the shape must be obtained from the available data. The interval end point approach is used for it. Here, an interval for data measurement is first of all decided and vocabulary of words is built. Then interval end point data is collected from a group of subjects involving a two step process:

- Randomization of the words
- Survey of a group of subjects to provide end point data for the words on the scale.

Once the data is collected for the interval end points, mean and standard deviation are calculated for each end point and for each label (word) used in the vocabulary. Then plots are constructed for the mean and standard deviations for all the labels. Then if there is a gap between the two word intervals, then either a new word is inserted in between them or a combination of the two intervals is done together to construct a new label out of the two. Then minimum number of labels required using which the complete range of vocabulary of words can be modelled. However the basic problem inherent with the approach is that the shape of FOU must be chosen ahead of time and if all the uncertainty disappears, IT2 FS word model does not reduce to T1 FS model. Interval approach (IA) combines the good points of both the approaches.

Interval Approach (IA)[14]: It maps each subject's data interval into a pre-specified T1 person MF and to interpret the latter as an embedded T1 FS of an IT2 FS. IA consists of two parts: the data part and the FS part.

1) Data part: Here, the data in the form of intervals $[a^{(i)}, b^{(i)}]$, i=1,2,.........n is collected for a word from a group of n subjects. Pre-processing is done of the n data intervals.

1.1Data Pre-processing: It consists of four steps:

1.1.1. Bad data processing: The step involves removal of undesired data which is generally the one that falls outside the interval or gives no information.

1.1.2. Outlier processing [13]: These are selected using the Box and whisker test. Outliers are the points that are either more than 1.5 IQR above the third quartile or less than 1.5 IQR below the first quartile.

1.1.3. Tolerance limit processing: Here, the tolerance factor "k" is taken into account along with the mean and standard deviations for the left end point, right end point and length of the interval.

1.1.4. Reasonable interval processing: This is a very important step because it takes into account the fact that "words may also mean same thing to different people". Thus, overlapping data intervals are found and those that overlap to a certain extent based on particular criteria are accepted else rejected.

1.2 *Computing statistics for each interval:* After pre-processing of the data intervals is done, then is the time to calculate the mean and standard deviation for the available data intervals. Assuming the uniform data distribution, these statistics are calculated for all the m data intervals obtained finally at the output of the data pre-processing stage above i.e. $S_i = (m_Y^{(i)}, \sigma_Y^{(i)})$ where i=1, 2,........m.

2) *Fuzzy set (FS) part:* Once the data interval statistics are decided, now is the main task of building the plots for the data intervals. The data to be mapped is estimated to fall into one of the four regions: the interior FOU, left shoulder FOU, right FOU or the unreasonable region. This step further involves a number of steps as:

2.1. Selection of a T1 FS model: This is required for mapping of the data interval into the T1 MF values.

2.2. Calculating the value of the FS uncertainty measurement units: Here the mean and the standard deviation are chosen as the measures for the FS uncertainty measure.

2.3. Calculating the uncertainty measures for the T1 FS models: Here, the mean and standard deviations are calculated for the interior, left and right shoulder T1 MFs.

2.4. Computing the general formulae for the parameters of the T1 FS models: This step involves calculating the values of the end points of the intervals in terms of the general parameters for the normal distribution for the interior, left and right shoulder MF.

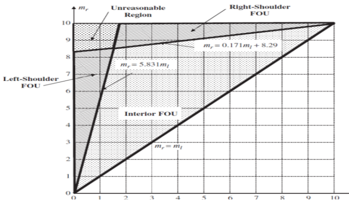

Fig 7: Plot of FOU after application of "t"test

2.5. Plotting the FOU: The step works on the basic principle that of all the available data intervals, all should either fall into the interior FOU, left shoulder FOU or the right shoulder FOU. Also, equations are derived for establishing the plot of interior FOU, left shoulder FOU and right shoulder FOU. This also involves the application of the t test. The plot is obtained is shown in fig.7.

2.6. Calculation of embedded T1 FS: After making a decision about the kind of FOU for a specific word, then is the task of mapping each of the remaining m data intervals into the respective T1 FSs. However, these FSs are the embedded T1 FSs. These are denoted by $W^{(i)}$. They help in establishing the FOU of the word.

2.7. Deletion of the prohibited T1 FSs: This step involves deletion of the FSs that fall outside the interval range i.e. say the interval taken for measurement is [0,10]. Then all those data intervals $[a^{(i)}, b^{(i)}]$ s.t. $a^{(i)} \leq 0$ and $b^{(i)} \geq 10$ are rejected. This further leads to the reduction in the number of embedded data intervals from m to m*.

2.8. Evaluating IT2 FS: The value of IT2 FS is computed as: $\widetilde{W} = \bigcup_{i=1}^{m^*} W^{(i)}$ $W^{(i)}$ are the just computed T1 FS.

B. CWW Engine [30],[26]

The role of CWW engine is to map the T1 FSs into IT2 FSs and generate FOU for corresponding set of words. The CWW engine does this work by establishing the nature of FOU & determining which word belongs to which FOU. This work is performed by building the mathematical model for FOU($\widetilde{W}$) [15]. To calculate the FOU, calculations are done to calculate the UMF and LMF. To draw the plot, following values have been computed:

$\underline{a}_{MF} \equiv \min_{i=1,\ldots\ldots,m^*}\{a_{MF}^{(i)}\}$ and $\overline{a}_{MF} \equiv \max_{i=1,\ldots\ldots,m^*}\{a_{MF}^{(i)}\}$

$\underline{b}_{MF} \equiv \min_{i=1,\ldots\ldots,m^*}\{b_{MF}^{(i)}\}$ and $\overline{b}_{MF} \equiv \max_{i=1,\ldots\ldots,m^*}\{b_{MF}^{(i)}\}$

$C_{MF}^{(i)} = \frac{a_{MF}^{(i)}+b_{MF}^{(i)}}{2}$, $\underline{C}_{MF} = \min \{C_{MF}^{(i)}\}$ and $\overline{C}_{MF} = \max \{C_{MF}^{(i)}\}$

where, the $a_{MF}^{(i)}$and$b_{MF}^{(i)}$ are the values for the lower and upper end of the respective data intervals respectively. The (p, μ_p) are the intersections of the right leg and the left leg of the left and right most extreme triangles. For the interior FOU, it has been seen that, the UMF plot is a trapezoidal one whereas the LMF plot is a triangular one as shown in Fig.8. The plot for Left shoulder FOU is shown in Fig.9 and the plot for the right shoulder FOU is shown in Fig.10.

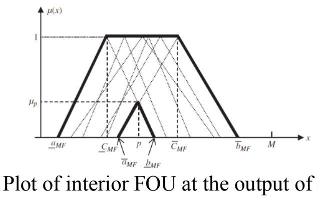

Fig 8: Plot of interior FOU at the output of decoder

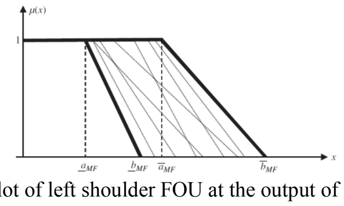

Fig 9: Plot of left shoulder FOU at the output of decoder

The three FOUs obtained above i.e. the interior, left shoulder and right shoulder FOU are called the canonical FOU.

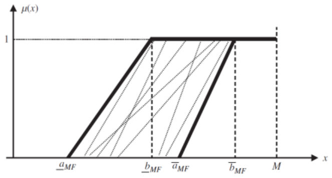

Fig 10: Plot of right shoulder FOU at the output of decoder

C. Decoder

The decoder performs the task of providing recommendations. The output of the decoder can be a word, ranking or a class. The word can be used in making social judgements. Social judgements are the ones that are used to take the decision about somebody's behaviour, personality, etc. The ranking method can be used to provide recommendations in situations such as procurements, etc. If a person wants to buy a product, out of various available options, it provides a ranking to the person that is based on the user needs, an order of ranking is generated to aid the person in decision making. Output can also be the class that can be used like in journal recommendations where the paper either is accepted or rejected, etc. The decoder also uses a number of similarity measures also such as Jaccard, Mitchell, etc.

D. Results/Recommendations

These are the outputs of the CWW engine that can be put to use in the decision making process.

IV. PROCESSOR FREQUENCY ADVISOR

We now design a Per-C, termed as Processor frequency advisor (PFA) with the aim that based on the user requirements; the Per-C suggests the user with the value of the system frequency that will be able to satisfy the user. We cater to the users' needs from a system by incorporating the "user satisfaction" as one of the criteria along with others. Users are required to provide the data input for different criteria. The input has been taken in the form of linguistic values because as pointed out earlier, humans generally express in terms of 'words' rather than numbers. In our system, we have modelled the user requirements from the system using the IT2 FSs as different users may have different satisfaction levels from the system related to the system display frequency. Although the HAPPE approach is good as it is user adaptive, but it depends on only two criteria i.e. the "performance" key the "power" key. The users can either step-up or step down the system frequency that too in discrete levels which is not the correct way to model the user needs. Here we model the user needs using the IT2 FSs. We further consider that the system can run in five frequencies shown in Table I. The algorithmic details of the Per-C are shown in Fig 11 below. We have termed the procedure as UFOPeC. We now demonstrate the working of this PFA with suitable numerical data. Various components of PFA shall now be explained one by one.

TABLE I: TYPICAL FUZZY TERMS FOR CORRESPONDING FREQUENCY VALUE OF PROCESSOR

Frequency (in GHz)	Fuzzy term assigned
0.8	Not satisfied
1.2	Somehow satisfied
1.6	Satisfied
2.2	Very satisfied
2.3	Over-satisfied

Algorithm: UFOPeC (User Feedback Optimized Per-C)

1. Define the problem statement and make the users aware of the problem details.
2. for i ← 1 to n
3. $[a^{(i)}, b^{(i)}]$← values for the lower end and upper end of the intervals
4. for i ← 1 to n
5. do if $0 \leq a^{(i)} \leq 10$ and $0 \leq b^{(i)} \leq 10$ and $b^{(i)} \geq a^{(i)}$then accept the interval.
6. else reject the interval.
7. for i← 1 to n'
8. compute the values of $Q_a, Q_b, Q_l IQR_a, IQR_b and IQR_l$ for all the end points.
9. for i← 1 to n'
10. do if $a^{(i)} \in [Q_a(0.25) - 1.5IQR_a, Q_a(0.75) + 1.5IQR_a]$ and $b^{(i)} \in [Q_b(0.25) - 1.5IQR_b, Q_b(0.75) + 1.5IQR_b]$ and $L^{(i)} \in [Q_L(0.25) - 1.5IQR_L, Q_L(0.75) + 1.5IQR_L]$ then accept the interval
11. else reject the interval.
12. for i← to m'
13. do if $a^{(i)} \in [m_l - ks_l, m_l + ks_l]$ and $b^{(i)} \in [m_r - ks_r, m_r + ks_r]$ and $L^{(i)} \in [m_L - ks_L, m_L + ks_L]$ then accept the interval.
14. else reject the interval.
15. Perform the reasonable interval test for all the m'' intervals and further reduce the number of intervals to m.
16. for i← 1 to m
17. do compute $S_i = (m_Y^{(i)}, \sigma_Y^{(i)})$
18. Select a T1 FS model
19. Perform the mapping of the mean and standard deviation calculated in step no 14 to the corresponding values for T1 FS uncertainty measures.
20. for i← 1 to m
21. do perform the mapping $m_{MF}^{(i)} = m_Y^{(i)} and \sigma_{MF}^{(i)} = \sigma_Y^{(i)}$
22. Draw the FOU for interior, left shoulder and right shoulder. Find out whether each of the point above falls in the interior, left shoulder or right shoulder FOU. Also, find out the embedded T1 FSs by calculating the values of $a_{MF}^{(i)} and b_{MF}^{(i)}$ corresponding to $m_{MF}^{(i)}$ and$\sigma_{MF}^{(i)}$.
23. for i← 1 to m
24. do if $a_{MF}^{(i)} \geq 0$ and $b_{MF}^{(i)} \leq 10$ then accept the interval as it is admissible.
25. else reject the interval
26. for i← 1 to m*
27. do calculate the IT2 FS as $\widetilde{W} = \cup_{i=1}^{m^*} W^{(i)}$
28. for i← 1 to m*
29. do compute the LMF, UMF and centroid values and draw the interior, left shoulder and right shoulder FOU as:
$$\underline{a}_{MF} \equiv \min_{i=1,\ldots\ldots,m^*}\{a_{MF}^{(i)}\}$$
$$\overline{a}_{MF} \equiv \max_{i=1,\ldots\ldots,m^*}\{a_{MF}^{(i)}\}$$
$$\underline{b}_{MF} \equiv \min_{i=1,\ldots\ldots,m^*}\{b_{MF}^{(i)}\}$$
$$\overline{b}_{MF} \equiv \max_{i=1,\ldots\ldots,m^*}\{b_{MF}^{(i)}\}$$
$$C_{MF}^{(i)} = \frac{a_{MF}^{(i)}+b_{MF}^{(i)}}{2}$$
$$\underline{C}_{MF} = \min\ \{C_{MF}^{(i)}\}$$
$$\overline{C}_{MF} = \max\ \{C_{MF}^{(i)}\}$$
30. Calculate the average values for the centroid using the NWA. Let the centroid intervals be as $[c_r^i, c_r^i]$. Calculate the uncertainty in the centroid values as: $\delta^i = \frac{c_r^i - c_r^i}{2}$.
31. Compare the δ^i values for different parameters and rank the systems or criteria to aid in the decision making process.

Fig 11: Algorithmic description of PFA

Encoder for PFA

We now give the details of the associated the fuzzy terms with the system frequency. Fuzzy logic can be introduced into the system at a number of places. Our system model and the related details are explained below. The working of the system is governed in terms of three actions:

Action 1 (a1): if the user is "not satisfied" with the system performance, the user presses the performance key.

Action 2 (a2): if the user is "satisfied" with the system performance, the user does not press any key.

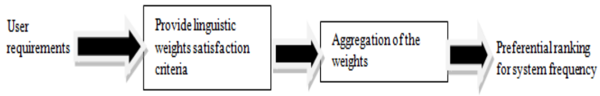

Fig 12: Frequency value advisor

Action 3 (a3): if the user is "over-satisfied" with the system performance, i.e. the user is satisfied with the current system performance and still wants to conserve the system energy, then the user presses the power key. For example, the user satisfaction may be based on a number of criteria such as:

Criteria 1 (c1): screen brightness

Criteria 2 (c2): battery life indicator (software application used in the HAPPE)

Criteria 3 (c3): type of application run on the system

Criteria 4 (c4): amount of time spent by the user on the system while the application is running. We can also assign linguistic weights to the criteria as given in the Table II below.

TABLE II: CRITERIA AND THEIR LINGUISTIC WEIGHTS

Criteria	Linguistic Weight
Screen brightness (c1)	Very low
	Low
	Medium
	High
	Extremely high
Battery life indicator	Low
	Medium
	High
Type of application	Absolutely uninteresting
	Somewhat interesting
	Fairly Interesting
	More interesting
	Absolutely interesting
Amount of time spent	Very Less
	Less
	Comparable
	Large
	Very large

We now develop a Per-C based system consisting of encoder, CWW engine and decoder. The encoder generates IT2 FSs on the basis of the data input for the various criteria by the user of the system. The task of the CWW engine is to take the requirements of the user along-with linguistic weights [25],[24] for the criteria for producing a ranking for the user to decide the user's suitable system frequency. We have conducted a survey on 10 users. Table III summarizes data outputs at various stages of the study.

CWW engine for Processor Frequency Advisor

We will use the mean of centroid method to generate the ranking for the criteria. Thus, by using the centroid data and calculating the NWAs [20], [21] for the intervals, we get the following values for the centroids for the respective criteria as: Screen brightness is [5.293, 7.207] with centroid mean as 6.2502and deviation about the mean is 0.680798, for battery indicator is [5.467, 7.814] with centroid mean as 6.640333and deviation about the mean as1.173333, for type of application is [4.484, 6.631] with centroid mean as 5.5572and deviation about mean as 1.0736and amount of time spent is [4.484, 6.631] with centroid mean as 5.5572 and deviation about mean as 1.0736.

Decoder for Processor Frequency Advisor

The criteria screen brightness is the best criteria to judge the user satisfaction as it has the minimum deviation about the centroid. Thus, associating the corresponding terms for the screen brightness i.e. Very low, Low, Medium, High, Extremely high with the system frequencies (in GHz) i.e. 0.8, 1.2, 1.6, 2.2, 2.3 it can be seen that taking the uncertainty about the centroid as the criteria, we generate the following ranking for the system from highest user satisfaction frequency to the lowest satisfaction frequency all in GHz: 1.6, 2.2, 2.3, 1.2 and 0.8. The whole procedure for the modelling the user feedback using IT2 FSs has been summarized in the form of the algorithm, shown in its pseudo- code form in the Algorithm-1 below. We term this algorithm as user feedback optimized perceptual computer (UFOPeC) [27],[28],[29]. A brief explanation on the working of the same is as: Step 1 involves defining the problem statement to the user and making the user aware of the problem domain and what are the constraints, etc. Steps 2 and 3 involve taking the input from the user into the assumed the interval of measurement says [0, 10]. Steps 4 to 6 involve bad data processing leads to reduction in number of intervals from n to n'. . Steps 7 to 11 involve calculation of the following values: $Q_a(Q_b, Q_l)$ and IQR_a (IQR_bandIQR_l are the quartiles and inter-quartile ranges for left (right) end point and interval length respectively. These are the outlier processing leads to the number of intervals reduced to m' from n'. Steps 12 and 13 involve tolerance limit processing, where k being the tolerance factor and lead to the number of intervals reduced to m'' from m'. Step 14 involves performing the reasonable interval test onto the intervals so as to find out the overlapping intervals. Steps 15 and 16 involve calculation of the mean and standard deviation for all the data points to be used later for establishing the nature of data. Step 17 involves selection of T1 FS model suitable to the problem. Step 18 starts with the mapping of the mean and standard deviation to the T1 FS uncertainty measures. Ultimately the step 21 involves calculation of the FOU and mapping of each point into anyone of the FOU i.e. interior, left shoulder or right shoulder FOU. Steps 22 to 24 involve rejection of inadmissible T1 FSs thereby reducing the number of intervals to m*. Steps 25 and 26 involve calculation of IT2 FS by the union of the computed embedded T1 FS. Step 28 involves drawing the FOUs. Step 29 involves calculation of the average centroid value and uncertainty about the centroid. Last step involves the comparison of the uncertainty values and generation of the rankings for the system frequency.

Unlike the HAPPE approach, where there are no explicit criteria for specifying the user satisfaction, we have modelled the system in such a way that criteria have been specified for specifying the user satisfaction. Also, the last two steps involves finding out that out of all the criteria available, which one is the one that best gives us an idea of the user satisfaction. On the basis of this ranking, we can provide the user with the suggestion as to which system frequencies in order are suited to the user needs.

TABLE III: DATA INTERVALS AND END POINT STATISTICS FOR THE WORDS CHOSEN IN THE VOCABULARY

Criteria	Word	Pre-processing stage				FS part	left end statistics		right end statistics	
		Stage 1(n')	Stage 2(m')	Stage 3(m'')	Stage 4(m)	m*	m_l	s_l	m_r	s_r
Screen brightness (c1)	Very low	10	9	9	7	7	0.115	0.1244	0.563	0.133
	Low	10	9	9	6	4	0.263	0.2092	0.847	0.131
	Medium	10	10	9	7	7	1.626	0.1606	2.094	0.157
	High	10	9	9	7	7	1.82	0.1582	2.431	0.108
	Extremely high	10	9	9	8	8	2.225	0.1358	2.5	1E-04
Battery life indicator	Low	10	9	9	6	4	0.263	0.2092	0.847	0.131
	Medium	10	10	9	7	7	1.626	0.1606	2.094	0.157
	High	10	9	9	7	7	1.82	0.1582	2.431	0.108
Type of application	Absolutely uninteresting	10	9	9	7	7	0.012	0.0293	0.471	0.172
	Somewhat interesting	10	10	9	6	6	0.601	0.1185	1.039	0.083
	Fairly Interesting	10	9	9	7	7	1.063	0.1326	1.561	0.147
	More interesting	10	10	9	5	5	1.591	0.1482	2.106	0.192
	Absolutely interesting	10	10	9	7	7	1.902	0.1323	2.361	0.148
Amount of time spent	Very Less	10	9	9	7	7	0.012	0.0293	0.471	0.172
	Less	10	10	9	6	6	0.601	0.1185	1.039	0.083
	Comparable	10	9	9	7	7	1.063	0.1326	1.561	0.147
	Large	10	10	9	5	5	1.591	0.1482	2.106	0.192
	Very large	10	10	9	7	7	1.902	0.1323	2.361	0.148

TABLE IV: **FOU** FOR THE WORDS SHOWN IN THE ABOVE TABLE. EACH UMF AND LMF REPRESENTS A TRAPEZOID

criteria	Word	LMF					UMF				Centroid		Mean of centroid	Uncertainty about the centroid
		a	b	c	d	height	a	b	c	d	c_l	c_r		$\pm\delta$
Screen brightness (c1)	Very low (SVL)	0	0	0.2	2	0.126422	0	0	1.5	4.3	0.7	1.7	1.177	1.606
	Low (SL)	2.1	2.5	2.5	3	0.31732	0.4	1.8	3.3	5.1	1.4	3.9	2.6444	1.2595
	Medium (SM)	7.6	7.9	7.9	8	0.960809	4.8	6.9	8.8	11	6.2	9.4	7.7792	0.517
	High (SH)	8.4	11	11	12	0.126422	5.2	9.7	11	11	8.8	10	9.4996	0.6545
	Extremely high (SEH)	11	11	11	12	0.126422	7.8	11	11	11	9.4	11	10.1552	0.748
Battery life indicator	Low (BL)	2.1	2.5	2.5	3	0.31732	0.4	1.8	3.3	5.1	1.4	3.9	2.6444	1.2595
	Medium (BM)	7.6	7.9	7.9	8	0.960809	4.8	6.9	8.8	11	6.2	9.4	7.7792	1.606
	High (BH)	8.4	11	11	12	0.126422	5.2	9.7	11	11	8.8	10	9.4996	0.6545
Type of application	Absolutely uninteresting(AU)	0	0	0.1	1.4	0.126422	0	0	0.6	4.3	0.5	1.6	1.0615	0.5775
	Somewhat interesting (SI)	3.1	3.6	3.6	5	0.469027	1.1	3	4.4	6	2.5	4.7	3.5761	1.089
	Fairly Interesting (FI)	5.3	5.6	5.6	8	0.676359	2.6	5	6.6	9	3.9	7.7	5.764	1.892
	More interesting (MI)	7.5	8	8	8.5	1	4.8	7.2	8.5	11	6.6	9.1	7.8342	1.2155
	Absolutely interesting (AI)	8.4	11	11	11	0.126422	5.7	9.1	11	11	9	10	9.5469	0.594
Amount of time spent	Very Less (VLE)	0	0	0.1	1.4	0.126422	0	0	0.6	4.3	0.5	1.6	1.0615	0.5775
	Less(LE)	3.1	3.6	3.6	5	0.469027	1.1	3	4.4	6	2.5	4.7	3.5761	1.089
	Comparable(C)	5.3	5.6	5.6	8	0.676359	2.6	5	6.6	9	3.9	7.7	5.764	1.892
	Large (LA)	7.5	8	8	8.55	1	4.8	7.2	8.5	11	6.6	9.1	7.8342	1.2155
	Very large	8.4	11	11	11	0.126422	5.7	9.1	11	11	9	10	9.5469	0.594

V. CONCLUSION

In our present work, we have proposed a new algorithm viz. UFOPeC (user feedback optimized perceptual computing) for obtaining the optimal power efficiency in adaptive computing systems that can run at multiple operating frequencies/voltages. Our approach models the user satisfaction very well and more realistically as compared to than the other existing mechanisms like in [1] as we have taken the user feedback in terms of words and modelled the same using the IT2 FSs (interval type-2 fuzzy sets). An appropriate numerical example has been chosen to demonstrate the design of our model. A computing with words/Per-C based user feedback collection model for controlling the processor power efficiency is introduced. Needless to say that CWW/Per-C is a very efficient tool in modelling human perceptions. Here the objects of computation are the words drawn from natural language instead of numbers. Perceptions alone don't make the sole criteria rather the backed logic of reasoning is also a supportive tool in the same scenario. Our future research shall aim for more robust implementation of the Per-C model with a significant number of user profiling for running processor power efficient mobile computing applications.

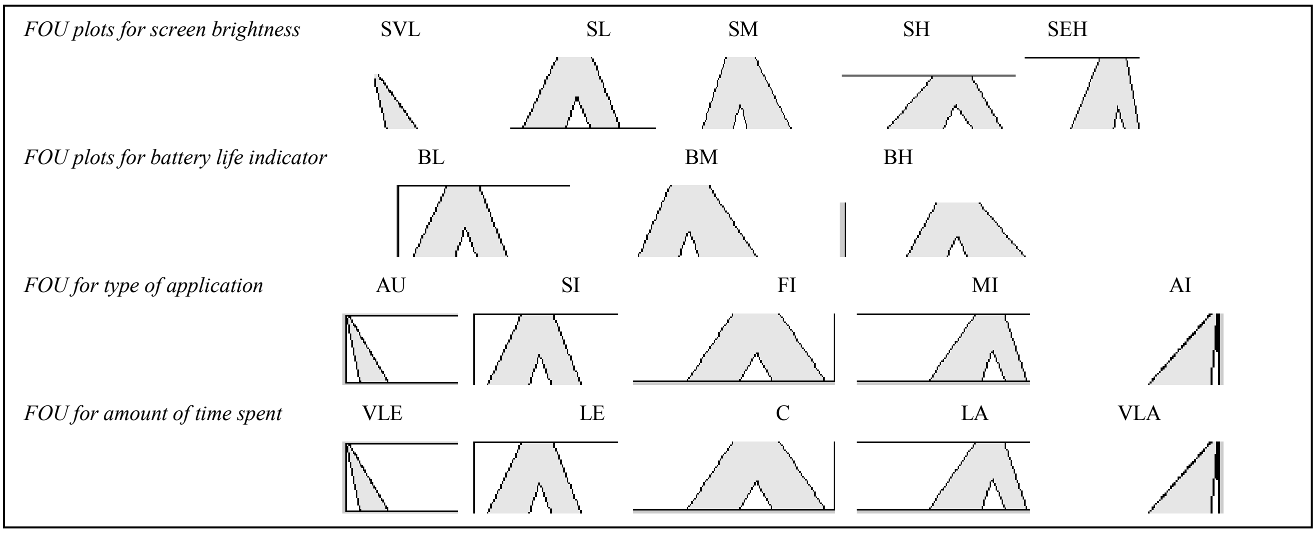

Fig. 13 : Plots of the FOUs for some of the words

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