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Fuzzy Logic-based Multicriteria Decision Making Approach for Improved Perception of Distributed Multimedia

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Abstract. Although the problem of multimedia application-level performance is closely linked to both the user perspective of the experience as well as to the service provided by the underlying network, it is rarely studied from an integrated viewpoint. To alleviate this problem in the context of a multimedia application, a method is proposed in this paper for obtaining a priority order of low-level Quality of Service parameters, which would ensure that user level Quality of Perception is maintained at an optimum level. This approach provides a series of advantages over previous attempts, in that it allows us to exploit the results of extensive Quality of Perception tests to absolve the users from the necessity of specifying their preferences, but at the same time offers users the added flexibility of indicating their perceived media priorities, should they differ from the default values. Moreover, our approach is also capable to handle inconsistencies that may occur in the formulation of such priorities. Lastly, since Quality of Perception is a more inclusive measure of the human multimedia experience, this is a more comprehensive approach than preceding attempts. Our current work is focused on expressing preferences by fuzzy sets and on the provision of improved solving techniques.

1 Introduction

The focus of our research has been the enhancement of the traditional, technical view of Quality of Service (QoS) with a user-level defined Quality of Perception (QoP). This is a measure, which encompasses not only a user's satisfaction with multimedia clips, but also his/her ability to perceive, synthesise and analyse the informational content of such presentations. As such, in previous work we have investigated the interaction between QoP and QoS and its implications from both a user perspective [3], as well as a networking angle [4].

Although the problem of multimedia application-level performance is closely linked to both the user perspective of the experience as well as to the service provided by the underlying network, it is rarely studied from an integrated viewpoint. Clearly, this is a very unsatisfactory state of affairs, and indeed the literature itself reveals relatively few instances of research being done in the area of bridging the application-network gap. Usually, three approaches are suggested in the literature. The first approach tries to bridge the application-network gap implicitly. By this it is understood that there is no explicit mapping between application-level user requirements and the QoS provided by the network. What happens rather is that the user specifies, usually through a Graphical User Interface, his/her desired presentation quality. This approach usually assumes a technically-aware user capable of specifying parameters such as desired playback frame rate, spatial resolution, or acceptable synchronisation delay between the audio and video streams. In the second approach an explicit mapping linking application-level user requirements to network QoS is actually given. Such a mapping can either be defined on a per layer basis or directly between application and network-level parameters. The last approach is, in essence, a more restrictive version of the first. What happens here is that the user is played short-duration probes of differing qualities of the multimedia material in question and (s)he then specifies which of the given sample qualities is acceptable. Thus, any choice that the user might make in as far as desired multimedia quality goes is guaranteed to be delivered - at least in the initial stages - by the network.

We have addressed the problem of bridging the application-network gap from a multi-attribute decision-making perspective, using the Analytic Hierarchy Process. We have sought to use this approach to integrate results from our work on Quality of Perception with the more technical characterisation of Quality of Service, with an ultimate aim of providing an adaptable communications protocol geared towards human requirements in the delivery of distributed multimedia.

2 Evaluating User-perceived Quality of Service

Our approach to evaluating user-perceived QoS (QoP) has been mainly empirical, as is dictated by the fact that its primary focus is on the human-side of multimedia computing. What has been done is that users from diverse backgrounds (test subjects involved academics, students, secretaries, businessmen) and ages (12-58 years old) were presented with a set of 12 short (30 - 45 seconds' duration) multimedia clips in MPEG-1 format. These were chosen to be as varied as possible, ranging from a relatively static news clip to a highly dynamic rugby football sequence. All of them depicted excerpts from real world programs and thus represent informational sources, which an average user might encounter in everyday life. Each clip was shown with the same set of QoS parameters, unknown to the user. After each clip, the user was asked a series of questions (ranging from 10 to 12) based on what had just been seen and the experimenter duly noted the answers. Lastly, the user was asked to rate the quality of the clip that had just been seen on a scale of 1 - 6 (with scores of 1 and 6 representing the worst and, respectively, best-perceived qualities possible).

Because of the relative importance of the audio stream in a multimedia presentation as well as the fact that it takes up an extremely low amount of bandwidth compared to the video it was decided to transmit audio at full quality during the experiments. Parameters were, however, varied in the case of the video stream. These include both spatial parameters (such as colour depth) and temporal parameters (frame rate). Accordingly, two different colour depths were considered (8 and 24-bit), together with 3 different frame rates (5, 15 and 25 frames per second - fps). Twelve users have been tested for each (*frame_rate*, *colour_depth*) pair. In summary the results (see [3] for a more detailed coverage) obtained in the QoP experiments show that:

- A significant loss of frames (that is, reducing the frame rate) does not proportionally reduce the user's understanding and perception of the presentation. In fact, in some instances (s)he seemed to assimilate more information, thereby resulting in more correct answers to questions. This is because the user has more time to view a frame before the frame changes (at 25 fps, a frame is visible for only 0.04 sec, whereas at 5 fps a frame is visible for 0.2 sec), hence absorbing more information. This observation has implications on resource allocation.
- User assimilation of the informational content of clips is characterised by the *wys<>wyg* (what you see is not what you get) relation. What this means is that often users, whilst still absorbing information correctly, do not notice obvious cues in the clip. Instead the reasoning process by which they arrive at their conclusions is based a lot on intuition and past experience.
- Users have difficulty in absorbing audio, visual and textual information concurrently. Moreover, if the user perceives problems with the presentation (such as lip synchronisation) users will disregard them and focus on the audio message if that is considered to be contextually important. This implies that critical and important messages in a multimedia presentation should be delivered in only one type of medium, or, if delivered concurrently, should be done so with maximal possible quality.
- Highly dynamic scenes, although expensive in resources, have a negative impact on user understanding and information assimilation. Questions in this category obtained the least number of correct answers. However the entertainment value of such presentations seems to be consistent, irrespective of the frame rate at which they are shown. The link between entertainment and content understanding is therefore not direct and this is further confirmed by the second observation above.

All these results indicate that technical-oriented QoS must also be specified in terms of perception, understanding and absorption of content - Quality of Perception in short - if multimedia presentations are to be truly effective.

2.1 A Framework for QoP Adaptation

Distributed guaranteed services need to incorporate capabilities for responding to QoP and QoS changes originating from the user/applications or the system/network. To achieve these changes, the networked multimedia system will require fast renegotiation protocols and adaptive mechanisms. The renegotiation protocols will rely on dependable and simple monitoring and recognition algorithms to detect requests for QoS changes or system degradations. The envisioned adaptive mechanisms should include update mechanisms for resource allocation in response to detection of system degradation. The challenge will be to make monitoring, detection and adaptation mechanisms efficient and fast [8].

The *Dynamically Reconfigurable Stacks Project* (DRoPS) provides an infrastructure for the implementation and operation of multiple adaptable protocols [2]. The core architecture is embedded within the Linux operating system, is accessible through standard interfaces, such as *sockets* and the UNIX *ioctl* (I/O control) system calls, has direct access to network devices and benefits from a protected, multiprogramming environment. The architecture allows additional QoS maintenance techniques, such as flow shaping (to smooth out bursts in traffic), at the user or interface level, and transmission queue scheduling, at the device queue level.

DRoPS-based communication protocols are composed of fundamental mechanisms, called *microprotocols*, which perform arbitrary protocol processing operations. The complexity of processing performed by a microprotocol is not defined by DRoPS and may range from a simple protocol function, such as a checksum, to a complex layer of a protocol stack, such as TCP. In addition, protocol mechanisms encapsulated within a microprotocol may be implemented in hardware or software. If appropriate hardware is available, the microprotocol merely acts as a wrapper, calling the relevant hardware function. Microprotocols are encapsulated in loadable modules, allowing code to be dynamically loaded into a running operating system and executed without the need to recompile a new kernel. Each such microprotocol can be implemented via a number of adaptable functions. For instance, an acknowledgement protocol can be implemented either as an Idle Repeat Request or a Per Message Acknowledgement Scheme.

3. User-centred Design with Multi-criteria Constraints

In linking perceptual considerations with low-level technical parameters, the design process should take into account the subjective judgement of the end-user. The end-user may not clearly specify a desired parameter value and prefers the use of linguistic phrases to describe the objectives, e.g. *"A is equally important as B"*; *"A is slightly more important than B"*, or more complicated ones, such as *"How much more preferable is a flow control protocol when compared to a checksum algorithm with respect to obtaining a satisfactory audio quality?"*; *"How important is a specific acknowledgement scheme for user perception of video?"*. This does result in inherent imprecision. Although information about questions like the previous ones is vital in making correct design decisions, it is very difficult, if not impossible, to quantify them correctly, i.e. the main problem is how to quantify the linguistic choices selected by the decision-maker during the evaluation of the pairwise comparisons. All methods that use this approach eventually express the qualitative answers of a decision-maker into some numbers.

To this end, we have applied Saaty's Analytical Hierarchy Process (AHP) formalism [9] to obtain a method which, from combined user-, application- and network-level requirements, ultimately results in a protocol configuration specifically tailored for the respective user-needs. Thus, within the QoP framework, each multimedia application can be characterised by the relative importance of the video (*V*), audio (*A*) and textual (*T*) components as conveyors of information, as well as the dynamism (*D*) of the presentation. This is in accordance with the experimental QoP results obtained which emphasise that multimedia QoP varies with: the number of media flows, the type of medium, the type of application, and the relative importance of each medium in the context of the application. On the other hand, 5 network level QoS parameters have been considered in our model: bit error (*BER*), segment loss (*SL*), segment order (*SO*), delay (*DEL*) and jitter (*JIT*). Together with the *V*, *A*, *T* and *D* parameters these constitute, in Saaty's terminology, the *criteria* on the basis of which an appropriate tailored communication protocol is constructed. In DRoPS, the functionality of this protocol is realised through a number of 9 microprotocols, spanning 4 broad functionality classes [4].

By applying Saaty's methodology we obtain a total of 10 matrices. To this end, the decision-maker (both the designer and the user) has to express his/her opinion about the value of a single pairwise comparison at a time. Nine of these matrices give the relative importance of the various microprotocols (*alternatives*, in Saaty's vocabulary) with respect to the criteria identified in our model, while the last of these matrices details *pairwise comparisons* between the criteria themselves.

$$ALTwrtBER = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1/3 & 1/7 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1/3 & 1/7 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1/3 & 1/7 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1/3 & 1/7 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1/3 & 1/7 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1/3 & 1/7 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1/3 & 1/7 \\ 3 & 3 & 3 & 3 & 3 & 3 & 3 & 1 & 1/5 \\ 7 & 7 & 7 & 7 & 7 & 7 & 7 & 5 & 1 \end{bmatrix} \quad (1)$$

The formulation of the 10 matrices has been based on the results of the experiments described in Section 2. An example of one of the former type of matrices, i.e. of the different alternatives with respect to one of the criteria (bit error rate in this case) is given in Relation (1). Each entry a_{ij} of the matrix *ALTwrtBER* defines the numerical judgement made by the designer and/or the user in comparing criterion to criterion. Psychological experiments have shown that individuals cannot simultaneously compare more than 7 objects (±2) [5]. Thus, usually, pairwise comparisons are quantified by using a scale of nine grades, which describe the relative importance of the criteria [9]. If a_{ij} is a point on this nine-point scale, i.e. a_{ij} $\in$ {1,2,3,...,8,9}, then $a_{ji} = 1/a_{ij}$ also holds [9]. For example, in Relation (1) the judgement *"microprotocol A is equally important as microprotocol B with respect to BER"* corresponds to a weighting of $a_{ij} = 1$, while the judgement *"microprotocol A is absolutely more important than microprotocol B"* would correspond to a value of $a_{ij} = 9$. Intermediate terms can also be assigned when compromise is needed between two adjacent characterisations. Note that in Relation (1), the considered microprotocols are, in order {*no sequence control, strong sequence control, no flow control, window-based flow control, IRQ, PM-ARQ, no checksum algorithm, block* *checking, full Cyclic Redundancy Check*}. For example, as far as bit error rate is concerned (see Relation (1)), the only microprotocols that have an impact upon it are the checksum algorithms. The strongest of these methods, the full CRC, has the highest weight (a value of $a_{ij} = 7$) in comparison with all the others, while a relatively weak block checking algorithm is considered to be *moderately more important* (α_{8j}=3, j=1,2,…,7) than microprotocols from other functionality classes.

While all the previous nine matrices considered have a constant form, the matrix of each criterion with respect to all the other criteria named *CRwrtCR*, shown below, is the only one whose values may fluctuate as a result of changes in the operating environment, as well as a consequence of changes in *user preferences* and *perceptions*. Relation (2) provides an instance of this matrix used in our model; the respective criteria are, in order, *BER, SO, SL, DEL, JIT, V, A, T* and *D*.

$$CRwrtCR=\begin{bmatrix} 1 & 1/2 & 1 & 1/4 & 1 & | & 2 & 4 & 4 & 3 \\ 2 & 1 & 1 & 1/4 & 1/3 & | & 5 & 4 & 5 & 4 \\ 1 & 1 & 1 & 1/3 & 1/2 & | & 4 & 6 & 4 & 4 \\ 4 & 4 & 3 & 1 & 5 & | & 6 & 7 & 6 & 5 \\ 1 & 3 & 2 & 1/5 & 1 & | & 4 & 6 & 6 & 6 \\ - & - & - & - & - & + & - & - & - & - \\ 1/2 & 1/5 & 1/4 & 1/6 & 1/4 & | & 1 & 1/2 & 3 & 2 \\ 1/4 & 1/4 & 1/6 & 1/7 & 1/6 & | & 2 & 1 & 3 & 2 \\ 1/4 & 1/5 & 1/4 & 1/6 & 1/6 & | & 1/3 & 1/3 & 1 & 1 \\ 1/3 & 1/4 & 1/4 & 1/5 & 1/6 & | & 1/2 & 1/2 & 1 & 1 \end{bmatrix} \quad (2)$$

An average user, though, would have difficulty in *a priori* judgement of varying technical parameters such as delay, jitter, error and loss rates on highly subjective attributes such as perception, understanding and satisfaction. Whilst this is true for QoS attributes at the level of the transport service, users are better able to quantify their requirements in terms of more abstract characteristics like the prioritisation of core multimedia components such as *V*, *A* and *T*. The matrix in Relation (2) reflects this situation and could conceptually be split-up into 4 sub-matrices, which are:

- A 5×5 matrix, in the upper left part of the matrix in Relation (2), giving the relative importance of the *BER, SO, SL, DEL* and *JIT* criteria with respect to one another. This matrix changes dynamically during the course of the transmission of a multimedia clip. An example illustrating this behaviour is presented in Section 5.
- A 4×4 matrix, located in the bottom right of the matrix given by (2). Here, user input can reflect personal choices of the relative importance of the video, audio and textual components in the context of the application, as well as a relative characterisation of the dynamism of the multimedia clip. Whilst, these values can be changed dynamically depending on the visualised scene, *a priori* values in this case could reflect the result of user- consultations. This indeed is the case with our QoP experiment [3], where a broad base of people were polled about their opinions for a wide range of clips with a variety of subject matter (action movie, animated movie, band, chorus, commercial, cooking, documentary, news, pop music, rugby, snooker, weather forecast). Thus, users characterised the News clip

as being relatively static, i.e. dynamism is *Low*, and considered that the video and audio media components conveyed a *High* informational load, in contrast to the text component which was judged to have a *Medium* informational weight.

- A 5×4 matrix and a 4×5 (one of which is the transpose of the other) which reflect designer choices of the relative importance of the five QoS parameters considered on *V, A, T* and *D.* The elements of these matrices remain fixed at run-time, and, in our particular case, reflect the results of our previous work on QoP [3].

Following the AHP, the weights w_i, i=1,…9 denoting the relative importance of each criterion i among the p criteria (p=9) are evaluated using the formula:

$$w_i = \frac{\left(\prod_{j=1}^{p} a_{ij}\right)^{1/p}}{\sum_{i=1}^{p}\left(\prod_{j=1}^{p} a_{ij}\right)^{1/p}} \quad i = 1,2,\ldots,p \tag{3}$$

and a higher priority setting corresponds to a greater importance.

Pairs among alternatives are also compared with respect to the ith criterion and then a weight $w_{j,i}$, which denotes how preferable is the alternative j with respect to the criterion i, is derived. As previously, there is a total of p pairwise comparisons in the matrix and weights are calculated following Relation (3). The weighted sum model, [10], is used to find the preference of an alternative j with respect to all criteria simultaneously; preference is defined by P_j and denotes the overall priority, or weight, of action j:

$$P_j = \sum_{i=1}^{p} w_i \cdot w_{j,i} \tag{4}$$

In the maximisation case, the best alternative is the one that possesses the highest priority value among all others.

4. Multi-criteria Decision-Making and the Fuzzy Programming Method

Intelligent decision making in the construction of communication protocols is achieved by adopting the AHP formalism, described in the previous section, which is one of the most popular methods of the Multi-criteria Decision-Making (MCDM). Due to the nature of our problem, where the objective-technical information provided by the designer and the subjective-perceptual information supplied by the user could form inconsistent judgement matrices, the need to apply a weight determination technique suitable to handle inconsistencies was indispensable. Therefore, the Fuzzy Programming Method (FPM), which is a method capable to solve even high inconsistent matrices, was used.

The FPM proposed by Mikhailov and Singh [7] is an approach capable to handle inconsistent pairwise comparison judgement matrices, where the judgements can be expressed either as crisp, intervals or fuzzy numbers. Each reciprocal pairwise comparison matrix, $A=[\alpha_{ij}]\in\Re^{n\times n}$, can be represented as a system of $m = n(n-1)$ linear equalities:

$$R\times w = 0, \tag{5}$$

where n is the number of elements compared, w is the vector of weights and $R\in\Re^{n\times n}$. For the inconsistent cases, the method is finding a solution that approximately satisfies Equation (5), i.e. $R\times w \approx 0$.

One of the most important advantages of the FPM is that the prioritisation problem is reduced to a fuzzy programming problem that can be easily formulated and solved as a standard linear program:

$$\begin{aligned} &\text{Obj.: } \max \lambda \\ &\text{s.t. } \lambda d_k + R_k w \le d_k,\ k = 1,\ldots, m,\ 1 \ge \lambda \ge 0 \\ &\sum_{i=1}^{n} w_i = 1\ ,\quad w_i > 0,\ i = 1,\ldots, n \end{aligned} \tag{6}$$

where the values of the tolerance parameters d_k represent the admissible interval of approximate satisfaction of the crisp inequalities $R_k w < 0$. For the practical implementation of the FPM, it is reasonable all these parameters, d_k, to be set equal [1].

After deriving the underlying weights from the comparison matrices through the FPM technique, the local weights are synthesised following the Weight-Sum Model [10]. The overall value V_j of each j^{th} alternative, A_j, is expressed as:

$$V_j = \sum_{i=1}^{n} w_i r_{ij} \tag{7}$$

where w_i is the weight assigned to the i^{th} criterion and r_{ij} is the relative score of the alternative j on criterion i. Obviously, the alternative with the maximum overall value V_j will be chosen.

5. Application of the FPM to the Construction of Communication Protocols

The applicability of the proposed approach can be illustrated by means of a multimedia user scenario tested through simulation.

Table 1. Overall values of the alternative microprotocols for the experiment

Priorities	micro1	micro2	micro3	micro4	micro5	micro6	micro7	micro8	micro9
Initial	0.0982	**0.1684**	0.0922	0.1361	0.0847	0.1279	0.0868	0.0674	0.1373
Updated	**0.1262**	0.1259	0.1154	0.1186	0.0819	0.1095	**0.1337**	0.0739	0.1251

In Table 1, our methodology has been applied to a situation where a delay sensitive multimedia application is being transmitted. The notation adopted in Table 1 is as follows: *no sequence control* (micro1)*, strong sequence control* (micro2)*, no flow control* (micro3)*, window-based flow control* (micro4)*, IRQ* (micro5)*, PM-ARQ* (micro6)*, no checksum algorithm* (micro7)*, block checking* (micro8)*, full Cyclic Redundancy Check* (micro9).

As a result of a delay-intolerant audio application being subjected to a period of high network delays, the upper left sub-matrix can reflect this situation by changing the numerical judgements to reflect a more radical bias in favour of the delay component. Accordingly, the matrix in Relation (2), has been changed to the one given below, in which row four of the upper left sub-matrix highlights the increased importance of the delay parameter with respect to the other QoS measures included in our model.

$$CRwrtCR = \begin{bmatrix} 1 & 1/2 & 1 & 1/7 & 1 & | & 2 & 4 & 4 & 3 \\ 2 & 1 & 1 & 1/7 & 1/3 & | & 5 & 4 & 5 & 4 \\ 1 & 1 & 1 & 1/7 & 1/2 & | & 4 & 6 & 4 & 4 \\ 7 & 7 & 7 & 1 & 6 & | & 6 & 7 & 6 & 5 \\ 1 & 3 & 2 & 1/6 & 1 & | & 4 & 6 & 6 & 6 \\ - & - & - & - & - & + & - & - & - & - \\ 1/2 & 1/5 & 1/4 & 1/6 & 1/4 & | & 1 & 1/2 & 3 & 2 \\ 1/4 & 1/4 & 1/6 & 1/7 & 1/6 & | & 2 & 1 & 3 & 2 \\ 1/4 & 1/5 & 1/4 & 1/6 & 1/6 & | & 1/3 & 1/3 & 1 & 1 \\ 1/3 & 1/4 & 1/4 & 1/5 & 1/6 & | & 1/2 & 1/2 & 1 & 1 \end{bmatrix} \quad (8)$$

In Table 1 we can see that the priorities of the different microprotocols obtained through our approach change from the initial configuration, biased towards microprotocol 2 (an overall value of 0.1684 was assigned to that microprotocol initially**)**, to an updated one in which microprotocols 7 and 1 are top of the priority ordering. This means that the priority ordering of the microprotocols would change to one, which favours microprotocols that do not lead to extra delays, as one would expect. In our case, these are represented by microprotocols 1 and 7.

6. Conclusions and Further Work

In the context of a multimedia application, a method is proposed for obtaining a priority order of low-level QoS parameters, which would ensure that user level QoP is maintained at an optimum level. This approach provides a series of advantages over previous attempts, in that it allows us to exploit the results of extensive QoP tests to absolve the users from the necessity of specifying their preferences, but at the same time offers users the added flexibility of indicating their perceived media priorities, should they differ from the default values. Moreover, our approach is also capable to handle inconsistencies that may occur in the formulation of such priorities. Lastly, since QoP is a more inclusive measure of the human multimedia experience, this is a more comprehensive approach than preceding attempts. Our current work is focused on expressing preferences by fuzzy sets and on the provision of improved solving techniques.

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