Bargaining-Based Rate Allocation for Non-Collaborative Multi-User Speech Communication Systems

Bengt J. Borgstrom
Department of Electrical Engineering
University of California, Los Angeles
jonas@ee.ucla.edu

Mihaela van der Schaar
Department of Electrical Engineering
University of California, Los Angeles
mihaela@ee.ucla.edu

Abeer Alwan
Department of Electrical Engineering
University of California, Los Angeles
alwan@ee.ucla.edu

ABSTRACT
We propose a novel rate allocation algorithm for multi-user speech communication systems based on bargaining theory. Specifically, we apply the generalized Kalai-Smorodinsky bargaining solution to allow varying bargaining powers for different speech signals. We estimate the level of voicing in the speech signals, and allocate higher rates to higher levels of voicing. The proposed system is developed to be applicable to any scalable speech coder and to be robust to a variety of quality metrics. We also generalized the algorithm to scenarios when individual users have unequally weighted priorities. Our system is shown to provide better performance than the baseline scheme of uniform rate allocation.

1. INTRODUCTION
Resource management is an important aspect of any speech communications system. For decades, much attention has been paid to rate allocation within cellular telephone networks. However, with the emergence of new modes of communication, such as internet phone services, rate allocation algorithms for speech communication systems have again become a crucial topic of research.

This paper focuses on a multi-user speech communication system with a central spectral moderator (CSM). The CSM is responsible for dynamically allocating rate to the M users in the network. In resource allocation scenarios, such as this, it is efficient to consider the concept of fairness between users in the utility domain, as opposed to the resource domain. In [1], the authors propose a rate control approach for generalized processor sharing that parameterizes a source model and allocates rate accordingly, but they do not consider the resulting utilities.

Existing resource allocation schemes based on utility measures often require a relatively simple utility function. In [2], the authors propose a rate allocation scheme for communication networks based on utility results, but the scheme requires the utility function to be solvable with Lagrangian optimization techniques.

In this paper, we propose a non-collaborative rate allocation algorithm based on axiomatic bargaining theory. Specifically, we will apply the Kalai-Smorodinsky bargaining solution to the rate allocation problem. Bargaining theory has previously been shown to provide improved performance in optimization problems, such as rate allocation in multimedia networks and power allocation in communication networks [3].

The novelty of this paper lies in the fact that we apply bargaining theory to speech communication networks. Solving the rate allocation problem in the utility domain may prove extremely convenient for speech communication due to the complexity of speech quality metrics. Additionally, there is no generally favored numerical speech quality measure, and our proposed algorithm is robust to a variety of metrics. Another novelty of our paper is the fact that rate allocation is performed without knowledge of external factors such as power constraints or channel conditions. Instead, the algorithm relies solely on the characteristics of the speech signals to be transmitted.

An important feature of the proposed system is the robustness of the algorithm to different speech coders and different speech quality metrics. The rate allocation algorithm derived in this paper is compatible with any speech encoder, as long as the output bitstream is scalable to some extent.

In Section 2, we describe bargaining theory fundamentals. Section 3 includes an overview of the speech communication system. Section 4 will discuss the application of general bargaining theory to the system. In Section 5 we describe the calculation of bargaining parameters. We will provide a finalized solution in Section 6. Section 7 briefly analyzes the complexity of the algorithm. Section 8 shows the performance of the overall system. Finally, conclusions and discussion are provided in Section 9.

2. BARGAINING THEORY
2.1 Axiomatic Bargaining Theory
In its simplest form, the notion of bargaining is a general and intuitive idea. In [4], bargaining is defined as a prob-

lem involving two parties, who can cooperate toward the creation of a commonly desirable surplus, over whose distribution both parties are in conflict. In this basic problem definition, the surplus referred to is in bargaining theory labeled *resources*, and the benefit of the surplus to each party is labeled *utility.* A central theme to early bargaining solutions is the idea of Pareto efficiency. If a solution is Pareto efficient, it must then satisfy collective rationality properties [4]. It therefore must also lie on the Pareto Surface, which is defined as the collection of points in utility space relative to which no other solutions are superior in all objectives [5].

The development of Axiomatic Theory of Bargaining in [6] introduced a more mathematical approach to the solution. In axiomatic bargaining theory, a solution is selected that satisfies a set of rational and desirable axioms, and these axioms guarantee fairness among parties. Specifically, this theory presented the *normalized* bargaining problem, in which the problem is represented by the pair $(S, \mathbf{d})$ in utility space. In this notation, S is the the subset of the utility space which includes all feasible utility points, and $\mathbf{d}$ is the *disagreement point*, which represents the point in the utility space below which no efficient solutions exist. Specifically:

$$\mathbf{d} = \left[u_1^{min}, u_2^{min}, \ldots, u_M^{min}\right]^T, \tag{1}$$

where u_i^{min} represents the minimum agreeable utility for user i.

2.2 The Kalai-Smorodinsky Bargaining Solution

The Kalai-Smorodinsky Bargaining Solution (KSBS) introduced the concept of a *utopia point*, $\mathbf{a}$, which is a point in the utility space that represents a desired but unrealistic agreement. The utopia point is defined as:

$$\mathbf{a} = \left[u_1^{max}, u_2^{max}, \ldots, u_M^{max}\right]^T, \tag{2}$$

where u_i^{max} represents the maximum achievable utility for user i and is only achievable if all the rate is allocated to that user.

The KSBS therefore defines the unique solution to a normalized bargaining problem as the intersection of the Pareto Surface and the line connecting $\mathbf{d}$ and $\mathbf{a}$. The KSBS also offers the ability to apply the concept of *bargaining powers*, which represent the weights of individual party's demands in bargaining.

The unique KSBS to the bargaining problem represented by $(S, \mathbf{d})$ [7], is defined as:

$$KSBS = \max_{\mathbf{x} \in S,\ \alpha \in R} \mathbf{x} = \mathbf{d} + \alpha C \cdot (\mathbf{a} - \mathbf{d}), \tag{3}$$

where C is a diagonal matrix whose c_{ii} element is the bargaining power of the i^{th} party. Figure 1 shows an example of the KSBS, labeled as (u_1^*, u_2^*), in the simple 2-party case.

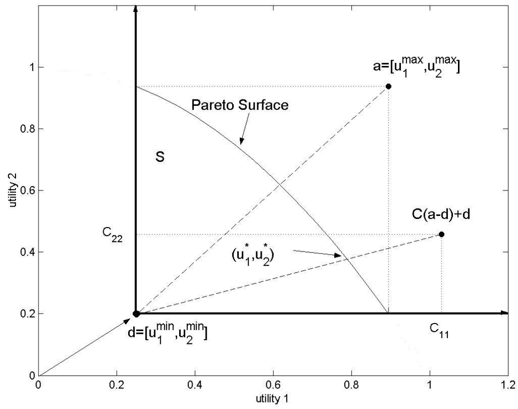

Figure 1: *The KSBS for a 2-user case*

3. PROPOSED RATE ALLOCATION SYSTEM

This paper will focus on a multi-user speech communication system with a central spectral moderator (CSM) for the M-user case. The CSM is responsible for dynamically allocating a constant total rate, R, to the users. That is, for every block iteration, the CSM will determine the rate allocation vector:

$$\mathbf{q}_k = \left[r_{1,k}, r_{2,k}, \ldots, r_{M,k}\right]^T, \tag{4}$$

where $r_{i,k}$ represents the rate allocated to the k^{th} block of user i, for $1 \leq i \leq M$ and $k \geq 1$. Note the following constraints on $\mathbf{q}_k$:

$$0 \leq r_i \leq R, \ for\ 1 \leq i \leq M, \quad and\ k \geq 1, \tag{5}$$

$$and \sum_{i=1}^{M} r_{i,k} = R, \ for\ k \geq 1. \tag{6}$$

Let $\mathbf{B}_{i,k}$ represent the k^{th} block of coded speech from user i. The CSM then applies the rate allocation scheme to the coded speech blocks by scaling $\mathbf{B}_{i,k}$ and transmitting only the first $r_{i,k}$ bits. Let $\widehat{\mathbf{B}}_{i,k}$ represent the truncated version of $\mathbf{B}_{i,k}$. Figure 2 shows the system overview for the 2-user case. In this figure, $BP_{i,k}$ represents the bargaining power of user i for block k.

The CSM of our proposed system determines the rate allocation vector $\mathbf{q}_k$ with the following steps:

1. Determine the matrix C by normalizing the bargaining powers of the individual users:

$$c_{ii} = \frac{BP_{i,k}}{\sum_{m=1}^{M} BP_{m,k}}. \tag{7}$$

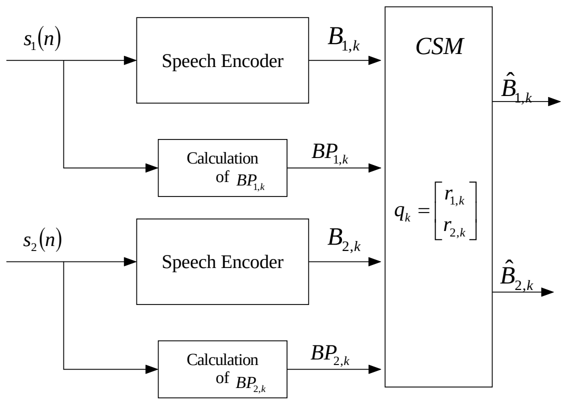

Figure 2: *System Overview for 2-User Case*

2. Define the Pareto Surface (see Section 5.1).
3. Position the disagreement point (see Section 5.2).
4. Determine $\widehat{\mathbf{u}}_k$, the KSBS in the utility space (see Section 6).
5. Determine the point in the resource domain, $\widehat{\mathbf{q}}_k$, corresponding to $\widehat{\mathbf{u}}_k$ (see Section 6).

It is important to note that the rate allocation algorithm developed in this paper can be applied to many different encoders. As can be seen in Figure 2, the only requirement for the coder used is that the output bit stream is scalable. Furthermore, better performance of our rate allocation scheme can be expected with finer granularity in the scalability of the encoder. We implement a simple Code-Excited LPC (CELP) encoder [8] to illustrate the performance of our system.

Although the proposed algorithm rate allocation algorithm is designed to be robust to any multi-rate speech coder, the performance of the system is limited by the bitrate resolution of the speech coder. A speech coder with a large number of bitrate modes will result in a highly populated Pareto Surface, and will therefore result in more possible Pareto-optimal bargaining solutions.

Finally, in this paper we do not address channel effects. That is, the coded speech blocks are assumed to be transmitted and received without any packet loss.

4. APPLICATION OF BARGAINING THEORY TO RATE ALLOCATION

In order to apply axiomatic bargaining theory to the rate allocation problem, certain aspects of the general normalized bargaining problem need to be defined in terms of speech processing and communication theory. Firstly, the concept of resources can clearly be defined as allocated rate to each user in the system. Additionally, the concept of utility can be defined as the perceptual quality of speech transmitted by each user. Finally, the concept of bargaining power can be interpreted as relative importance of additional rate for a given user to transmit a given level to speech quality.

4.1 The Utility Function

In general bargaining theory, the utility function is a transformation from the resource domain to the utility domain. In the specific case of our system, the utility function expresses the quality of speech encoded at a certain bit rate. Thus, our utility transformation can be generalized as $U : \Phi \to \Omega$, where Φ and Ω represent the resource and utility domains respectively, and $\Phi, \Omega \subset R_{+}^{M}$.

Traditional signal processing distortion metrics are not ideal for speech signals due to the fact that human hearing is a highly complex and nonlinear system. We therefore propose to use the Itakura distortion metric [9]. The Itakura distortion, $I_s(s,r)$, between the original speech signal, $s(n)$, and synthesized speech encoded at a bit rate r, $\widehat{s}_r(n)$, is defined as:

$$I_s(s,r) = \log\left(\frac{\widehat{\mathbf{a}}^T \cdot R_p \cdot \widehat{\mathbf{a}}}{\mathbf{a}^T \cdot R_p \cdot \mathbf{a}}\right) \tag{8}$$

where R_p is the p^{th}-order autocorrelation matrix of $s_r(n)$, and $\mathbf{a}$ and $\widehat{\mathbf{a}}$ are defined as:

$$\mathbf{a} = [1, -a_1, -a_2, \ldots, -a_p]^T, \tag{9}$$

and

$$\widehat{\mathbf{a}} = [1, -\widehat{a}_1, -\widehat{a}_2, \ldots, -\widehat{a}_p]^T \tag{10}$$

where a_k and $\widehat{a}_k$ are the k^{th} predictor coefficients for p-order LPC analysis of $s(n)$ and $\widehat{s}(n)$, respectively.

In order to obtain a utility function that is directly related to benefit, we define our proposed utility function as the inverse of the Itakura distortion. Thus, our utility transformation is given by:

$$U(\mathbf{q}_k) = \left[\frac{1}{I_s(r_{1,k})}, \frac{1}{I_s(r_{2,k})}, \ldots, \frac{1}{I_s(r_{M,k})}\right]. \tag{11}$$

An important property required for applying the KSBS to our problem of rate allocation is the fact that our utility function is $\mathbf{d}$-*comprehensive*. The definition of comprehensiveness of a set states that the set $S \subset R^M$ is $\mathbf{d}$-*comprehensive* if $y \in S$ and $d \leq x \leq y$ imply $x \in S$.

It can be proven that our utility space is $\mathbf{d}$-*comprehensive*:

- Let $x, y \in R^{M\times 1}$ be vectors in the utility space such that $d \leq x \leq y$.
- Now define $r_y \in R^{M\times 1}$ such that $y = U(r_y)$.

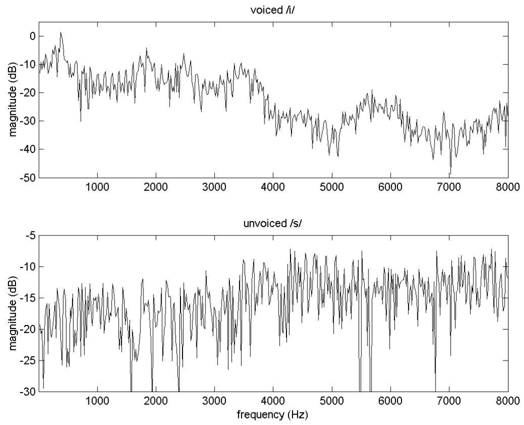

Figure 3: *Log-Spectra of Voiced and Unvoiced Speech*

- Since our utility function is monotonically increasing, there must exist a vector $r_x \in R^{M \times 1}$ such that $x = U(r_x)$.
- Thus, $x \in S$.

4.2 Voicing as a Bargaining Power

Application of the KSBS to our problem of rate allocation necessitates the definition of bargaining powers. We hypothesize that due to the greater amount of energy present in voiced speech relative to unvoiced speech, voiced speech would benefit to a greater extent, in terms of perceptual quality, from additional rate. Additionally, due to the complexity of the spectra of voiced speech relative to the spectra of unvoiced speech, voiced speech would benefit more from from additional rate. Examples of the log-spectra of voiced and unvoiced speech are shown in Figure 3. Due to the presence of strong formant frequencies in voiced speech, the corresponding log-spectra show multiple peaks. The location and bandwidth of these peaks are very important for the perception of speech. In contrast, unvoiced speech contains weak resonant frequencies.

In order to define bargaining powers based on the level of voicing in speech, we are required to determine an algorithm for voiced-unvoiced classification. Voiced speech usually contains higher low-frequency energy than unvoiced speech [10], and thus the low-band to high-band energy ratio is often a good indication of the level of voicing of speech. The low-band to high-band energy ratio of the speech signal $s(n)$ is defined as:

$$\Gamma = \frac{\sum_{n=1}^{N} s_{lpf}^{2}(n)}{\sum_{n=1}^{N} s_{hpf}^{2}(n)}, \tag{12}$$

where $s_{lpf}(n)$ and $s_{hpf}(n)$ represent the low-pass filtered and high-pass filtered versions of $s(n)$, respectively.

5. DERIVATION OF FORMULA FOR BARGAINING PARAMETERS

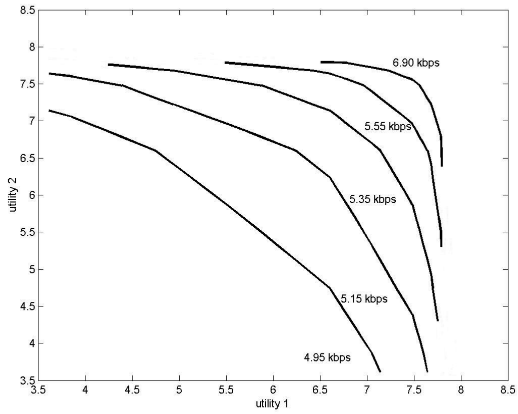

Figure 4: *Examples of Pareto Surfaces for Varying Total Rate in the 2-User Case*

5.1 Determining the Pareto Surface

Pareto optimal solutions are defined in [5] as points in the utility space relative to which no other solutions are superior in all objectives. Due to the monotonically decreasing nature of the rate-distortion curve of our speech encoder, we can assume that the Pareto surface, PS, of our system is comprised only of points in the utility space corresponding to allocation of all available rate. Thus, the Pareto Space will include all points corresponding to allocation of all rate, excluding those utility points relative to which there exist superior solutions. Specifically the definition of the Pareto Surface here is:

$$\begin{aligned} PS = \{\, \mathbf{u} \in \Omega \mid if\ \mathbf{u} = U(\mathbf{q})\ \forall \mathbf{q},\ and\ if \\ \tilde{\mathbf{u}} = \mathbf{u} - U(\mathbf{q} - \mathbf{e}_j),\ for\ 1 \le j \le M \\ then\ \tilde{u}_l \neq 0\ for\ 1 \le l \le M \,\}, \end{aligned} \tag{13}$$

where

$$\mathbf{e}_j(k) = \begin{cases} 1 & \text{if k=j} \\ 0 & \text{else} \end{cases}. \tag{14}$$

Figure 4 illustrates examples of Pareto Surfaces for various average rate constraints in the simple 2-user case.

5.2 Determining the Disagreement Point

The disagreement point, $\mathbf{d}_k$, represents the point in utility space below which no Pareto optimal solutions exist. It therefore follows from the definition of our Pareto Surface in Equation 14 that the disagreement point, $\mathbf{d} \in R^{1 \times M}$, should be positioned to be the maximum point that still includes all Pareto optimal solutions. In order to define the disagreement point, first let $G_i(\alpha) \subset R^M$ represent the plane in the utility space described by $u_i = \alpha$. Thus, the disagreement point can be defined as:

$$\mathbf{d} = [d_1, d_2, \ldots, d_M]^T, \tag{15}$$

where

$$d_i = min_{\{PS \cap G_i(\alpha) \neq 0\}} \alpha. \tag{16}$$

Note that the existence of $\mathbf{d}$ is not guaranteed, and that $\mathbf{d}$ only exists if the Pareto Surface defined in Equation 14 is non-empty. If $\mathbf{d}$ does not exist, the KSBS can not be calculated. This situation only arises when the total rate constraint is very high, so that the performance of the speech coder saturates and rate allocation schemes become meaningless. Therefore, in this trivial case, the proposed rate allocation algorithm is designed to simply allocate uniformly to the M users. However, in the non-trivial case when the total rate constraint is not excessive, the disagreement point $\mathbf{d}$ exists, and the bargaining-based rate allocation scheme is applicable.

5.3 Determining Bargaining Powers

5.3.1 Equal Priority Rate Allocation

In the most common scenario, all users in the M-user proposed network will have equal priority. In other words, the speech quality of the transmitted signal from user i is of equal importance to the overall system as the quality of speech of the transmitted signal of user j, for $1 \leq i, j \leq M$. The following section derives the formula for bargaining powers in the equal priority case.

In the general KSBS, the bargaining powers of individual users can be interpreted as the relative weights of the user's demands. In the mathematical solution of Equation 3, the bargaining powers of the users in the system are given by the matrix C. As stated previously, C is a diagonal matrix with the c_{ii} element representing the normalized bargaining power of user i.

As proposed earlier, we use the low-band to high-band energy ratio of the input speech signal of user i to determine the corresponding normalized bargaining power, which will be referred to as ρ_i. The Equation for the low-band to high-band energy of speech signal $s(n)$ is given by Equation 12.We now define C as:

$$C = diag\{\mathbf{p}\}, \tag{17}$$

where

$$\mathbf{p} = [\rho_1, \rho_2, \ldots, \rho_M]^T, \tag{18}$$

and where the individual bargaining powers ρ_i are given by:

$$\rho_i = \frac{\Gamma_i}{\sum_{m=1}^{M} \Gamma_m}. \tag{19}$$

5.3.2 Weighted Priority Rate Allocation

In certain possible scenarios, the priorities of different users in the M-user network may differ from each other at given times. This situation necessitates formula for weighted bargaining powers.

Let the vector $\mathbf{w} \in R^{M \times 1}$ contain the relative priority weights of the M individual users. That is:

$$\mathbf{w} = [w_1, w_2, \ldots, w_M]^T, \tag{20}$$

where w_i corresponds to the relative priority weight of user i. It then follows intuitively that , $\mathbf{p}_w$, the vector of normalized weighted bargaining power, can be calculated as follows:

$$\mathbf{p}_w = [\rho_1, \rho_2, \ldots, \rho_M]^T, \tag{21}$$

where

$$\rho_i = \frac{w_i \Gamma_i}{\sum_{m=1}^{M} w_m \Gamma_m}. \tag{22}$$

Note that when the priority weight vector is set to $\mathbf{w} = [1, 1, \ldots, 1]$, the formula in Equations 21 and 22 simplify to the equal priority case of Section 5.3.1.

6. THE FINALIZED KSBS FOR RATE ALLOCATION

With necessary bargaining parameters defined for our speech communication system, we can now apply our KSBS to the problem of rate allocation for multi-user speech transmission. Given the total rate constraint, we can define the Pareto Surface according to Equation 14. Furthermore, we can position our disagreement point according to Equation 15. Then, the Kalai-Smorodinsky bargaining solution can be stated simply as $\widehat{\mathbf{q}}$, where $\widehat{\mathbf{u}} = U(\widehat{\mathbf{q}})$, and where:

$$\widehat{\mathbf{u}} = argmax_{\mathbf{u}} \; \mathbf{p}^T \cdot \left(\frac{\mathbf{u} - \mathbf{d}}{|\mathbf{u} - \mathbf{d}|} \right), \tag{23}$$

for $\forall \mathbf{u} \in PS$.

Note that the transformation $U(\cdot)$ is not 1-to-1, and therefore there does not exist an inverse transform $U^{-1}(\cdot)$. Thus, in order to obtain a point in the resource domain, $\mathbf{q}_k$ such that:

$$\mathbf{u}_k = U(\mathbf{q}_k), \tag{24}$$

we rely on a predetermined codebook containing $(\mathbf{u}_k, \mathbf{q}_k)$ pairs to find our final rate allocation solution vector, $\widehat{\mathbf{q}}_k$. Our codebook is designed to not contain any mappings of distinct resource vectors, q_j and q_k, to the same utility vector, so that $u_l = U(q_j) = U(q_k)$.

7. COMPLEXITY ANALYSIS

The proposed rate allocation scheme uses a low complexity algorithm that can run in real-time. The KSBS algorithm for the M-user case involves the following computations at each block iteration:

- Calculating the low-band energy to high-band energy ratio of each user
- Normalizing the bargaining powers of each user
- Determining the solution in the utility domain
- Identifying the solution in the resource domain corresponding to the utility domain solution

Calculating the high-band to low-band energy ratio of a segment of speech requires filtering the speech with a low-pass filter. The low-pass filter would be followed by $N-1$ additions, where N represents the length of the speech block in samples, 1 subtraction to find the high-band energy, and 1 division. Normalization of the bargaining powers simply requires $M-1$ additions to determine the global denominator, followed by M divisions.

Determining the solution in the utility domain involves searching through a codebook to find the minimum result of a cost function. The calculation of the cost function, given in Equation 23, requires M subtractions, M multiplications, and 1 division. The actual size of the Pareto Surface grows exponentially as the number of users, M, increases. However, the Pareto Surface can be downsampled greatly without affecting the final results. In our simulations, we keep the size of the Pareto Surface under $PS < 1,000$. Thus, the search is not very extensive. For example, for the $M = 2$ user case the Pareto Surface consists of approximately $20-50$ pairs of corresponding resource and utility vectors. Additionally, once the solution in the utility domain has been located, the final solution in the resource domain can be easily looked up since the vectors are listed in pairs.

Furthermore, our algorithm does not require any additional buffering other than the buffering necessary for block-based speech coding. In our implementation, the input speech was windowed with a $25ms$ window. Thus, our rate allocation system can be run in real-time.

8. EXPERIMENTAL SET-UP AND RESULTS

The rate allocation algorithm developed in this paper was tested on the TIMIT continuous speech database. This database contains phonetically-balanced sentences spoken by multiple male and female speakers. The subset of the database used for our experiments consisted of 50 randomly chosen sentences by female speakers, and 50 randomly chosen sentences by male speakers.

We determined that the range of utility values corresponding to intelligible speech to be approximately $u > 3.00$. Thus, for data analysis, we normalized our results to more accurately describe the performance improvement relative to intelligible speech. Specifically, the normalized utility is determined by:

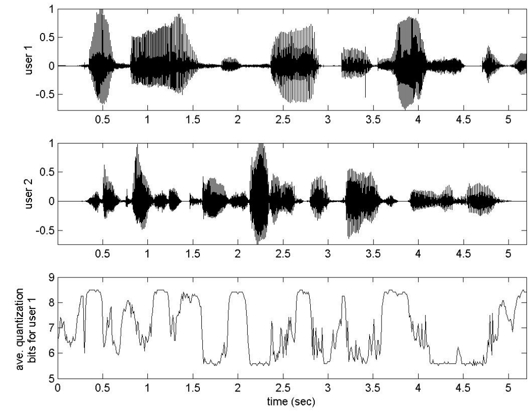

Figure 5: *Example of Bargaining-based Rate Allocation for Continuous Speech in the 2-User Case: The first two panels show the speech waveforms of the two users, and the third panel shows the average number of quantization bits per coded value for user* 1.

$$u^{'} = u - 3.00, \tag{25}$$

and the percent improvement is calculated by:

$$\%\, improvement = \frac{u_{new} - u_{old}}{u_{old} - 3.00}. \tag{26}$$

The system was tested on continuous speech with a varying number of users, M, at a constant total rate constraint of $M \cdot 5.40$ *kbps*. Figure 5 shows an example of rate allocation for the 2-user case, with the accompanying speech signals. Figure 6 shows the underlying relationship between the bargaining powers of the individual users, and the final allocated rate for the example in Figure 5.

For each value of M, sentences were chosen for each user, and the overall utility metric of the bargaining rate allocation solution was compared to that of the baseline solution of uniform rate allocation. Table 1 shows the performance of our total system compared to the baseline system in the case of continuous speech at $R = 5.40$ *kbps*. In this table, M refers to the number of users, $\overline{u}_{barg}$ refers to the mean utility obtained with the proposed bargaining solution, and $\overline{u}_{base}$ is the mean utility obtained with the baseline solution. As can be concluded from Table 1, our rate allocation algorithm provides superior performance to that of constant uniform allocation among the M users.

We then tested our rate allocation algorithm on simulated conversational speech. We concatenated randomly chosen spoken sentences with silence of length S_β, where S_β is a random variable with uniform distribution over the range $[0, \beta]$, and thus with an expected value of $E[S_\beta] = \beta/2$. Table 2 shows the results of our system on conversational speech for $R = 5.40$ *kbps* in the 2-user case. As can be concluded from the table, the proposed system leads to superior

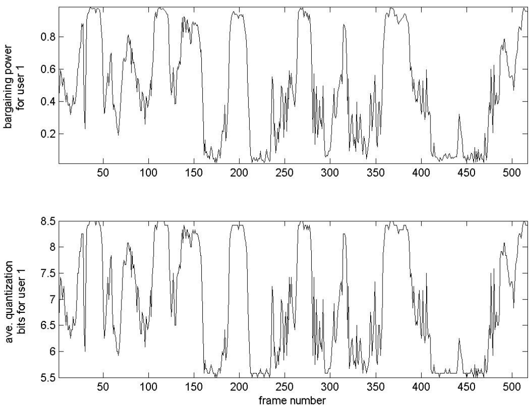

Figure 6: *Example of Relationship Between Bargaining Powers and the Resource Domain in the 2-User Case: The first panel shows the normalized bargaining power of user* 1*, and the second panel shows the corresponding average number of quantization bits per coded value.*

Table 1: *Performance of Overall Rate Allocation System for Continuous Speech at Fixed Rate of 5.40 kbps: Relative improvement is relative to a baseline system with uniform rate allocation.*

M	$\overline{u}'_{barg}$	$\overline{u}'_{base}$	% improvement
2	3.139	2.976	5.47%
3	2.750	2.616	5.12%
4	2.693	2.552	5.52%

performance for simulated conversational speech, relative to the baseline system. Additionally, the proposed system provides greater performance improvement for conversational speech than for continuous speech.

Figure 7 shows the rate-performance plot for our rate allocation system in the 2-user case, tested on simulated conversational speech with $E[S_\beta] = 1.0$ *sec*. As is shown in the figure, for a given speech quality measure of $u = 6.40$, the corresponding total average rate for the bargaining-based rate allocation system is $R_{barg} = 5.12$ *kbps* and the total average rate for the corresponding baseline system is $R_{base} = 5.40$ *kbps*. This can be interpreted as our proposed

Table 2: *Performance of Overall Rate Allocation System for* 2*-User Case for Conversational Speech at Fixed Rate of 5.40 kbps*

$E[S_\beta]$ (sec)	$\overline{u}'_{barg}$	$\overline{u}'_{base}$	% improvement
0	3.139	2.976	5.47%
0.5	3.380	3.076	9.88%
1.0	3.746	3.359	11.52%
1.5	3.872	3.365	15.07%

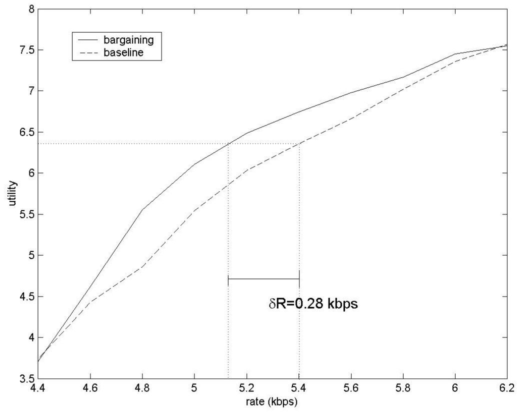

Figure 7: *Rate-Performance Plot for 2-User System with Conversational Speech*

Table 3: *Performance of Rate Allocation System for* 2*-User Weighted Priority Case, where the Priority Weight Vector,* $[x, y]^T$*, Contains the Relative Weights of the Bargaining Powers of the* 2 *Users*

Priority Weight Vector	$[1,1]^T$	$[1,2]^T$	$[1,3]^T$
R_1	5.336	5.161	5.064
R_2	5.444	5.639	5.736
$\overline{u}'_{1,barg}$	3.265	2.772	2.626
$\overline{u}'_{2,barg}$	3.150	3.206	3.373
% improvement for user 2	0.00%	1.78%	7.08%

system requiring approximately 5.5% less bandwidth than the baseline system for the given speech quality measure of $u = 6.40$.

As was discussed in Section 5.3.2, there may occur scenarios in which one or more users have higher bargaining powers. This situation was referred to as the *weighted priority* case. We tested our rate allocation algorithm on arbitrarily set priority weight vectors for the 2-user case. Table 3 shows our results for the *weighted priority* case.

Additionally, pilot perceptual experiments using the TIMIT sentence database demonstrated that there was noticeable perceptual difference between normalized utility scores that differed by $\Delta u > 0.5$.

9. CONCLUSIONS

In this paper, we focus on a non-collaborative multi-user speech communication system with a central spectral moderator. We investigate bargaining theory as a method of rate allocation in an M-user system, and apply the generalized KSBS to our system. The algorithm we develop uses the concept of bargaining powers based on the level of voicing in the speech signal to determine the optimal rate for each user. Specifically, we use voicing detection to estimate the level of voicing in each user's speech sample, and accordingly allocate rate. We also generalized the algorithm to scenarios when individual users have unequally weighted priorities. Our system is shown to provide better performance than the baseline scheme of uniform rate allocation. In the future, we will consider bargaining powers that can also be used for voiceless speech, and we will study the effects of packet loss.

10. REFERENCES

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