Leveraging Effective Query Modeling Techniques for Speech Recognition and Summarization

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Abstract

Statistical language modeling (LM) that purports to quantify the acceptability of a given piece of text has long been an interesting yet challenging research area. In particular, language modeling for information retrieval (IR) has enjoyed remarkable empirical success; one emerging stream of the LM approach for IR is to employ the pseudo-relevance feedback process to enhance the representation of an input query so as to improve retrieval effectiveness. This paper presents a continuation of such a general line of research and the main contribution is three-fold. First, we propose a principled framework which can unify the relationships among several widely-used query modeling formulations. Second, on top of the successfully developed framework, we propose an extended query modeling formulation by incorporating critical query-specific information cues to guide the model estimation. Third, we further adopt and formalize such a framework to the speech recognition and summarization tasks. A series of empirical experiments reveal the feasibility of such an LM framework and the performance merits of the deduced models on these two tasks.

1 Introduction

Along with the rapidly growing popularity of the Internet and the ubiquity of social web communications, tremendous volumes of multimedia contents, such as broadcast radio and television programs, digital libraries and so on, are made available to the public. Research on multimedia content understanding and organization has witnessed a booming interest over the past decade. By virtue of the developed techniques, a variety of functionalities were created to help distill important content from multimedia collections, or provide locations of important speech segments in a video accompanied with their corresponding transcripts, for users to listen to or to digest. Statistical language modeling (LM) (Jelinek, 1999; Jurafsky and Martin, 2008; Zhai, 2008), which manages to quantify the acceptability of a given word sequence in a natural language or capture the statistical characteristics of a given piece of text, has been proved to offer both efficient and effective modeling abilities in many practical applications of natural language processing and speech recognition (Ponte and Croft, 1998; Jelinek, 1999; Huang, *et al.*, 2001; Zhai and Lafferty, 2001^a; Jurafsky and Martin, 2008; Furui *et al.*, 2012; Liu and Hakkani-Tur, 2011).

The LM approach was first introduced for the information retrieval (IR) problems in the late 1990s, indicating very good potential, and was subsequently extended in a wide array of follow-up studies. One typical realization of the LM approach for IR is to access the degree of relevance between a query and a document by computing the likelihood of the query generated by the document (usually referred to as the query-likelihood approach) (Zhai, 2008; Baeza-Yates and Ribeiro-Neto, 2011). A document is deemed to be relevant to a given query if the corresponding document model is more likely to generate the query. On the other hand, the Kullback-Leibler divergence measure (denoted by KLM for short hereafter), which quantifies the degree of relevance between a document and a query from a more rigorous information-theoretic perspective, has been proposed (Lafferty and Zhai, 2001; Zhai and Lafferty, 2001^b; Baeza-Yates and Ribeiro-Neto, 2011). KLM not only can be thought as a natural generalization of the query-likelihood approach, but also has the additional merit of being able to accommodate extra information cues to improve the performance of document ranking. For example, a main challenge facing such a measure is that since a given query usually consists of few words, the true information need is hard to be inferred from the surface statistics of a query. As such, one emerging stream of thought for KLM is to employ the pseudo-relevance feedback process to construct an enhanced query model (or representation) so as to achieve better retrieval effectiveness (Lavrenko and Croft, 2001; Zhai and Lafferty, 2001^b; Tao and Zhai, 2006; Hiemstra *et al.*, 2004; Lv and Zhai, 2009; Carpineto and Romano, 2012; Lee and Croft, 2013; Clinchant and Gaussier, 2013).

Following this line of research, the major contribution of this paper is three-fold: 1) we analyze several widely-used query models and then propose a principled framework to unify the relationships among them; 2) on top of the successfully developed query models, we propose an extended modeling formulation by incorporating additional query-specific information cues to guide the model estimation; 3) we explore a novel use of these query models by adapting them to the speech recognition and summarization tasks. As we will see, a series of experiments indeed demonstrate the effectiveness of the proposed models on these two tasks.

2 Language Modeling Framework for IR

2.1 Kullback-Leibler Divergence Measure

A promising realization of the LM approach to IR is the Kullback-Leibler divergence measure (KLM), which determines the degree of relevance between a document and a query from a rigorous information-theoretic perspective. Two different language models are involved in KLM: one for the document and the other for the query. KLM assumes that words in the query are random draws from a language distribution that describes the information need of a user, and words in the relevant documents should also be drawn from the same distribution. The divergence of the document model with respect to the query model is defined by

$$\mathrm{KL}(Q \parallel D) = \Sigma_{w \in V} P(w \mid Q) \log \frac{P(w \mid Q)}{P(w \mid D)}. \tag{1}$$

KLM not only can be thought as a natural generalization of the traditional query-likelihood approach (Yi and Allan, 2009; Baeza-Yates and Ribeiro-Neto, 2011), but also has the additional merit of being able to accommodate extra information cues to improve the estimation of its component models (i.e., the query and document models) in a systematic way for better document ranking (Zhai, 2008).

Due to that a query usually consists of only a few words, the true query model $P(w|Q)$ might not be accurately estimated by the simple ML estimator (Jelinek, 1991). With the alleviation of this deficiency as motivation, there are several studies devoted to estimating a more accurate query modeling, saying that it can be approached with the pseudo-relevance feedback process. Such integration seems to hold promise for query reformulation (Carpineto and Romano, 2012; Lavrenko and Croft, 2001; Zhai and Lafferty, 2001[b]; Tao and Zhai, 2006). However, the success depends largely on the assumption that the set of top-ranked documents, $\mathbf{D}_{Top}=\{D_1,D_2,...,D_r,...\}$, obtained from an initial round of retrieval, are relevant and can be used to estimate a more accurate query language model.

2.2 Relevance Modeling (RM)

Under the notion of relevance modeling (RM, often referred to as RM-1), each query Q is assumed to be associated with an unknown relevance class R_Q, and documents that are relevant to the semantic content expressed in query are samples drawn from the relevance class R_Q. However, in reality, since there is no prior knowledge about R_Q, we may use the top-ranked documents $\mathbf{D}_{Top}$ to approximate the relevance class R_Q. The corresponding relevance model, on the grounds of a multinomial view of R_Q, can be estimated using the following equation (Lavrenko and Croft, 2001; Lavrenko, 2004):

$$P_{\mathrm{RM}}(w|Q) = \frac{\Sigma_{D_r \in \mathbf{D}_{Top}} P(D_r) P(w \mid D_r) \Pi_{w' \in Q} P(w' \mid D_r)}{\Sigma_{D''_r \in \mathbf{D}_{Top}} P(D''_r) \Pi_{w' \in Q} P(w' \mid D''_r)}, \tag{2}$$

where the prior probability $P(D_r)$ of each document can be simply kept uniform, while the document models (such as $P(w|D_r)$) are estimated with the ML estimator on the basis of the occurrence counts of w in each document, respectively.

2.3 Simple Mixture Model (SMM)

Another perspective of estimating an accurate query model with the top-ranked documents is the simple mixture model (SMM), which assumes that words in $\mathbf{D}_{Top}$ are drawn from a two-component mixture model: 1) One component is the query-specific topic model $P_{\mathrm{SMM}}(w|Q)$**,** and 2) the other is a generic background model $P(w|BG)$. By doing so, the SMM model $P_{\mathrm{SMM}}(w|Q)$ can be estimated by maximizing the likelihood over all the top-ranked documents (Zhai and Lafferty, 2001[b]; Tao and Zhai, 2006; Clinchant and Gaussier, 2013):

$$L = \prod_{D_r \in \mathbf{D}_{Top}} \prod_{w \in V} \left(\alpha \cdot P_{\mathrm{SMM}}(w \mid Q) + (1-\alpha) \cdot P(w \mid BG)\right)^{c(w,D_r)}, \tag{3}$$

where α is a pre-defined weighting parameter used to control the degree of reliance between $P_{\mathrm{SMM}}(w|Q)$ and $P(w|BG)$. This estimation will enable more specific words (i.e., words in $\mathbf{D}_{Top}$ that are not well-explained by the background model) to receive more probability mass, thereby leading to a more discriminative query model $P_{\mathrm{SMM}}(w|Q)$. Simply put, the SMM model is anticipated to extract useful word usage cues from $\mathbf{D}_{Top}$, which are not only probably relevant to the query Q, but also external to those already captured by the generic background model.

2.4 Regularized Simple Mixture Model (RSMM)

Although the SMM modeling aims to extract extra word usage cues for enhanced query modeling, it may confront two intrinsic problems. One is the extraction of word usage cues from $\mathbf{D}_{Top}$ is not guided by the original query. This would lead to a concern for SMM to be distracted from being able to appropriately model the query of interest, which is probably caused by some dominant distracting (or irrelevant) documents. The other is that the mixing coefficient α is fixed across all top-ranked documents albeit that different (either relevant or irrelevant) documents would potentially contribute different amounts of word usage cues to the enhanced query model. To mitigate these two problems, the original query model $P(w|Q)$ can be used to define a conjugate Dirichlet prior for the enhanced query model to be estimated; meanwhile, a trainable document-specific weighting coefficient α_{D_r} is introduced for each pseudo-relevant document D_r. The resulting model is referred to hereafter as the regularized simple mixture model (RSMM) and its associated objective likelihood function is expressed as (Tao and Zhai, 2006; Dillon and Collins-Thompson, 2010)

$$L = \prod_{w \in V} P_{\mathrm{RSMM}}(w \mid Q)^{\mu \cdot P(w|Q)} \times \\ \prod_{D_r \in \mathbf{D}_{Top}} \prod_{w \in V} \left(\alpha_{D_r} \cdot P_{\mathrm{RSMM}}(w \mid Q) + (1-\alpha_{D_r}) \cdot P(w \mid BG)\right)^{c(w,D_r)}, \tag{4}$$

where μ is a weighting factor indicating the confidence on the prior information (viz. the original query model).

3 The Proposed Modeling Framework

3.1 Fundamentals

It is obvious that the major difference among the representative query models mentioned above is how to capitalize on the set of top-ranked documents and the original query. Taking a step forward, several subtle relationships can be deduced through the following in-depth analysis. First of all, a direct inspiration of the LM-based query reformulation framework can be drawn from the celebrated Rocchio's formulation, while the former can be viewed as a probabilistic counterpart of the latter (Robertson, 1990; Ponte and Croft, 1998; Baeza-Yates and Ribeiro-Neto, 2011; Furui *et al.*, 2012; Carpineto and Romano, 2012). The basic idea of the Rocchio's formulation is to assign higher weights to those words more frequently occurring in the top-ranked documents. Building on the same idea, the LM-based query reformulation framework has been well studied and practiced in various IR tasks and shown excellent performance. Second, after some mathematical manipulation, the formulation of the RM model (*c.f.* Eq. (2)) can be rewritten as

$$P_{\mathrm{RM}}(w\,|\,Q) = \Sigma_{D_r \in \mathbf{D}_{Top}} P(w\,|\,D_r) \frac{P(Q\,|\,D_r)P(D_r)}{\Sigma_{D_r'' \in \mathbf{D}_{Top}} P(Q\,|\,D_r'')P(D_r'')}. \tag{5}$$

It becomes evident that the RM model is composed by mixing a set of document models $P(w|D_r)$. The mixing coefficients are estimated by normalizing the query likelihood $P(Q|D_r)$ with respect to each pseudo-relevant document D_r while the prior probability $P(D_r)$ of each document D_r is simply set to be uniform. As such, the RM model bears a close resemblance to the Rocchio's formulation. Furthermore, based on Eq. (5), we can recast the estimation of the RM model as an optimization problem, and the likelihood (or objective) function is formulated as

$$L = \prod_{w \in V} \left(\sum_{D_r \in \mathbf{D}_{Top}} P(w\,|\,D_r)P(D_r\,|\,Q) \right)^{c(w,Q)}, \qquad s.t. \sum_{D_r \in \mathbf{D}_{Top}} P(D_r\,|\,Q) = 1 \tag{6}$$

where the document models $P(w|D_r)$ are known in advance; the conditional probability $P(D_r|Q)$ of each document D_r is unknown and leave to be estimated. Therefore, the parameters needed to be estimated are the set of mixing coefficients (i.e., $P(D_r|Q)$) and then the RM model can be formed by linearly interpolated the models of pseudo-relevant documents weighted by their respective coefficients. Finally, a principled framework can be obtained to unify all of these query models by using a generalized objective likelihood function:

$$L = \prod_{w \in V} \prod_{E_i \in \mathbf{E}} \left(\sum_{M_r \in \mathbf{M}} P(w\,|\,M_r)P(M_r) \right)^{c(w,E_i)}, \qquad s.t. \sum_{M_r \in \mathbf{M}} P(M_r) = 1 \tag{7}$$

where **E** represents a set of observations which we want to maximize their likelihood, and **M** denotes a set of mixture components.

Building on the proposed framework, here we highlight how to infer several query modeling formulations from the framework:

1) **Relevance modeling**: when **E** only consists of the user query, **M** comprises a set of document models corresponding to the top-ranked (pseudo-relevant) documents, and we assume the document models are known, then it can be deduced to the RM model (*c.f.* Eq. (6)).

2) **Simple mixture modeling**: if we hypothesize that **M** consists of two components: one component is a generic background model and the other is an unknown query-specific topic model, the weight of each component is presumably fixed in advance, and the observations are those top-ranked documents (i.e., $\mathbf{E}=\mathbf{D}_{Top}$), then we will derive the SMM model in response to the objective function (*c.f.* Eq. (3)).

3) **Regularized simple mixture modeling**: if the weight of each component is required to be estimated as well and a Dirichlet prior is placed on the enhanced query model, the RSMM model can be obtained herewith (*c.f.* Eq. (4)).

4) **Others**: without loss of generality, some other state-of-the-art query models also can be deduced from the proposed general objective function, such as the three-mixture model (Zhang, *et al.*, 2002), the positional relevance model (Lv and Zhai, 2010), the cluster-based methods (Lee, *et al.*, 2008; Lee and Croft, 2013), and among others. Furthermore, the well-practiced topic modeling (Hofmann, 1999; Hofmann, 2001; Blei, *et al.*, 2003; Blei and Lafferty, 2009) can also be deduced from the unified framework.

As a consequence, the analysis made above reveals that all of these query models bear a close resemblance to one another, and can be deduced from Eq. (7) with different assumptions. In the following, we will further adopt and formalize such a framework to speech recognition and summarization.

3.2 Query-specific Mixture Modeling (QMM)

The SMM model and the RSMM model are intended to extract useful word usage cues from $\mathbf{D}_{Top}$, which are not only relevant to the original query Q but also external to those already captured by the generic background model. However, we argue in this paper that the "generic information" should be carefully crafted for each query due mainly to the fact that users' information needs may be very diverse from one another. To crystallize the idea, a query-specific background model $P_Q(w|\mathrm{BG})$ for each query Q can be derived from $\mathbf{D}_{Top}$ directly. Another consideration is that since the original query model $P(w|Q)$ cannot be accurately estimated, it thus may not necessarily be the best choice for use in defining a conjugate Dirichlet prior for the enhanced query model to be estimated. As an alternative, we propose to use the RM model as a prior to guide the estimation of the enhanced query model. The enhanced query model is termed query-specific mixture model (QMM), and its corresponding training objective function can be expressed as

$$\begin{aligned} L = & \prod_{w \in V} P_{\mathrm{QMM}}(w\,|\,Q)^{\mu \cdot P_{\mathrm{RM}}(w|Q)} \times \\ & \prod_{D_r \in \mathbf{D}_{Top}} \prod_{w \in V} \left(\alpha_{D_r} \cdot P_{\mathrm{QMM}}(w\,|\,Q) + (1-\alpha_{D_r}) \cdot P_Q(w\,|\,BG) \right)^{c(w,D_r)}. \end{aligned} \tag{8}$$

4 Applications

4.1 Query Modeling for Speech Recognition

Language modeling is a critical and integral component in any large vocabulary continuous speech recognition (LVCSR) system since it can be used to constrain the acoustic analysis, guide the search through multiple candidate word strings, and quantify the acceptability of the final output from the speech recognizer (Huang *et al.*, 2001; Jurafsky and Martin, 2008; Furui *et al.*, 2012). More concretely, the role of language modeling in LVCSR can be interpreted as calculating the conditional probability $P(w|H)$, in which H is a search history, usually expressed as a sequence of words $H=h_1, h_2,\ldots, h_L$, and w is one of its possible immediately succeeding words (i.e., an upcoming word). The *n*-gram model that follows a statistical modeling paradigm is the most prominently used in speech recognition because of the inherent simplicity and predictive power. Nevertheless, the *n*-gram model, aiming at capturing the local contextual information or the lexical regularity of a language, is inevitably faced with two fundamental problems. First, it is brittle across domains, since the performance is sensitive to changes in the genre or topic of the text on which it is trained. Second, it fails to capture the information (either semantic or syntactic) conveyed in the search history beyond the immediately preceding *n*-1 words when predicting an upcoming word. In view of those problems, over the years, several novel and ingenious methods have been developed to complement the *n*-gram models through dynamic language model adaptation.

Once the various aforementioned query modeling methods are applied to speech recognition, for a search history *H*, we can conceptually regard it as a query and each of its immediately succeeding words *w* as a (single-word) document. Then, we may leverage an IR procedure that takes *H* as a query and poses it to a retrieval system to obtain a set of top-ranked documents from a contemporaneous (or in-domain) corpus. Finally, the enhanced query model (that is $P(w|H)$ in speech recognition) can be estimated by RM, SMM, RSMM or QMM, and further combined with the background *n*-gram (e.g., trigram) language model to form an adaptive language model to guide the speech recognition process.

4.2 Query Modeling for Speech Summarization

On the other hand, extractive speech summarization aims at producing a concise summary by selecting salient sentences or paragraphs from the original spoken document according to a predefined target summarization ratio (Carbonell and Goldstein, 1998; Mani and Maybury, 1999; Nenkova and McKeown, 2011; Liu and Hakkani-Tur, 2011). Intuitively, this task could be framed as an ad-hoc IR problem, where the spoken document is treated as an information need and each sentence of the document is regarded as a candidate information unit to be retrieved according to its relevance to the information need. Therefore, the ultimate goal of extractive speech summarization could be stated as the selection of the most representative sentences that can succinctly describe the main theme of the spoken document. Similarly, based on the KLM, two different language models are involved in the selection processing: one for the whole document and the other for each sentence of the document. Therefore, KLM can be used to quantify how close the document *D* and one of its sentences *S* are: the closer the sentence model $P(w|S)$ to the document model $P(w|D)$, the more likely the sentence would be part of the summary. Then, the summary sentences of a given spoken document can be iteratively chosen from the spoken document in accordance with its corresponding divergence until the aggregated summary reaches a predefined (or target) summarization ratio.

Due to that each sentence *S* of a spoken document *D* to be summarized usually consists of only a few words, the corresponding sentence model $P(w|S)$ might not be appropriately estimated by the ML estimation. To alleviate the deficiency, we can leverage the merit of the above query modeling techniques to estimate an accurate sentence model (or representation) for each sentence to enhance the summarization performance.

5 Experimental Setup

The speech corpus consists of about 196 hours of Mandarin broadcast news collected by the Academia Sinica and the Public Television Service Foundation of Taiwan between November 2001 and April 2003 (Wang *et al.*, 2005), which is publicly available and has been segmented into separate stories and transcribed manually. Each story contains the speech of one studio anchor, as well as several field reporters and interviewees. A subset of 25-hour speech data compiled during November 2001 to December 2002 was used to bootstrap the acoustic model training. The vocabulary size is about 72 thousand words. The background language model was estimated from a background text corpus consisting of 170 million Chinese characters collected from the Chinese Gigaword Corpus released by LDC.

The dataset for use in the speech recognition experiments is compiled by a subset of 3-hour speech data from the corpus within 2003 (1.5 hours for development and 1.5 hours for test). The contemporaneous (in-domain) text corpus used for training the various LM adaptation methods was collected between 2001 and 2003 from the corpus (excluding the test set), which consists of one million Chinese characters of the orthographic broadcast news transcripts. In this paper, all the LM adaptation experiments were performed in word graph rescoring. The associated word graphs of the speech data were built beforehand with a typical LVCSR system (Ortmanns *et al.*, 1997; Young *et al.*, 2006).

In addition, the summarization task also employs the same broadcast news corpus as well. A subset of 205 broadcast news documents compiled between November 2001 and August 2002 was reserved for the summarization experiments (185 for development and 20 for test). A subset of about 100,000 text news documents, compiled during the same period as the documents to be summarized, was employed to estimate the related summarization models compared in this paper. We adopted three variants of the widely-used ROUGE metric (i.e., ROUGE-1, ROGUE-2 and ROUGE-L) for the assessment of summarization performance (Lin, 2003). The summarization ratio, defined as the ratio of the number of words in the automatic (or manual) summary to that in the reference transcript of a spoken document, was set to 10% in this research.

6 Experimental Results

In the first part of experiments, we evaluate the effectiveness of the various query models applied to the speech recognition task. The corresponding results with respect to different numbers of top-ranked documents being used for estimating their component models are shown in Table 1. Also worth mentioning is that the baseline system with the background trigram language model, which was trained with the SRILM toolkit (Stolcke, 2005) and Good-Turing smoothing (Jelinek, 1999), results in a Chinese character error rate (CER) of 20.08% on the test set. Consulting Table 1 we notice two particularities. One is that there is more fluctuation in the CER results of SMM than in those of RM. The reason might be that, for SMM, the extraction of relevance information from the top-ranked documents is conducted with no involvement of the test utterance (i.e., the query; or its corresponding search histories), as elaborated earlier in Section 2. When too many feedback documents are being used, there would be a concern for SMM to be distracted from being able to appropriate model the test utterance, which is probably caused by some dominant distracting (or irrelevant) feedback documents. The other interesting observation is that RSMM only achieves a comparable (even worse) result when compared to SMM. A possible reason is that the prior constraint of the

Table 1. The speech recognition results (in CER (%)) achieved by various language models along with different numbers of latent topics/pseudo-relevance feedback documents.

	16	32	64	128
Baseline	20.08			
Cache	19.86			
LDA	19.29	19.30	19.28	19.15
RM	19.26	19.26	19.26	19.26
SMM	19.19	19.00	19.14	19.10
RSMM	19.18	19.14	19.15	19.19
QMM	**19.05**	**18.97**	**19.00**	**18.99**

RSMM may contain too much noisy information so as to bias the model estimation. Furthermore, it is evident that the proposed QMM is the best-performing method among all the query models compared in the paper. Although the improvements made by QMM are not as pronounced as expected, we believe that QMM has demonstrated its potential to be applied to other related applications. On the other hand, we compare the various query models with two well-practiced language models, namely the cache model (Cache) (Kuhn and Mori, 1990; Jelinek *et al.*, 1991) and the latent Dirichlet allocation (LDA) (Liu and Liu, 2007; Tam and Schultz, 2005). The CER results of these two models are also shown in Table 1, respectively. For the cache model, bigram cache was used since it can yield better results than the unigram and trigram cache models in our experiments. It is worthy to notice that the LDA model was trained with the entire set of contemporaneous text document collection (*c.f.* Section 4), while all of the query models explored in the paper were estimated based on a subset of the corpus selected by an initial round of retrieval. The results reveal that most of these query models can achieve superior performance over the two conventional language models.

In the second part of experiments, we evaluate the utilities of the various query models as applied to the speech summarization task. At the outset, we assess the performance level of the baseline KLM method by comparison with two well-practiced unsupervised methods, viz. the vector space model (VSM) (Gong and Liu, 2001), and its extension, maximal marginal relevance (MMR) (Carbonell and Goldstein, 1998). The corresponding results are shown in Table 2 and can be aligned with several related literature reviews. By looking at the results, we find that KLM outperforms VSM by a large margin, confirming the applicability of the language modeling framework for speech summarization. Furthermore, MMR that presents an extension of VSM performs on par with KLM for the text summarization task (TD) and exhibits superior performance over KLM for the speech summarization task (SD). We now turn to evaluate the effectiveness of the various query models (viz. RM, SMM, RSMM and QMM) in conjunction with the pseudo-relevance feedback process for enhancing the sentence model involved in the KLM method. The corresponding results are also shown in Table 2. Two noteworthy observations can be drawn from Table 2. One is that all these query models can considerably improve the summarization performance of the KLM method, which corroborates the advantage of using them for enhanced sentence representations. The other is that QMM is the best-performing one among all the formulations studied in this paper for both the TD and SD cases.

Table 2. The summarization results (in F-scores) achieved by various language models along with text and spoken documents.

	Text Documents (TD)			Spoken Documents (SD)		
	ROUGE-1	ROUGE-2	ROUGE-L	ROUGE-1	ROUGE-2	ROUGE-L
VSM	0.347	0.228	0.290	0.342	0.189	0.287
MMR	0.407	0.294	0.358	0.381	0.226	0.331
KLM	0.411	0.298	0.361	0.364	0.210	0.307
RM	0.453	0.335	0.403	0.382	0.239	0.331
SMM	0.439	0.320	0.388	0.383	0.229	0.327
RSMM	0.472	0.365	0.423	0.381	0.235	0.329
QMM	**0.486**	**0.382**	**0.435**	**0.395**	**0.256**	**0.349**
SVM	0.441	0.334	0.396	0.370	0.222	0.326
QMM+ SVM	**0.492**	**0.395**	**0.448**	**0.398**	**0.261**	**0.358**

Going one step further, we explore to use extra prosodic features that are deemed complementary to the LM cue provided by QMM for speech summarization. To this end, a support vector machine (SVM) based summarization model is trained to integrate a set of 28 commonly-used prosodic features (Liu and Hakkani-Tur, 2011) for representing each spoken sentence, since SVM is arguably one of the state-of-the-art supervised methods that can make use of a diversity of indicative features for text or speech summarization (Xie and Liu, 2010; Chen *et al.*, 2013). The sentence ranking scores derived by QMM and SVM are in turn integrated through a simple log-linear combination. The corresponding results are shown in Table 2, demonstrating consistent improvements with respect to all the three variants of the ROUGE metric as compared to that using either QMM or SVM in isolation. We also investigate using SVM to additionally integrate a richer set of lexical and relevance features to complement QMM and further enhance the summarization effectiveness. However, due to space limitation, we omit the details here. As a side note, there is a sizable gap between the TD and SD cases, indicating room for further improvements. We may seek remedies, such as robust indexing schemes, to compensate for imperfect speech recognition.

7 Conclusion and Outlook

In this paper, we have presented a systematic and thorough analysis of a few well-practiced query models for IR and extended their novel applicability to speech recognition and summarization in a principled way. Furthermore, we have proposed an extension of this research line by introducing query-specific mixture modeling; the utilities of the deduced model have been extensively compared with several existing query models. As to future work, we would like to investigate jointly integrating proximity and other different kinds of relevance and lexical/semantic information cues into the process of feedback document selection so as to improve the empirical effectiveness of such query modeling.

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