Multi-Class Multi-Label Independent Model for Crowdsourcing

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ABSTRACT

Multi-Class Multi-Label Independent (MCMLI) model is a probabilistic generative model for truth inference in crowdsourcing. This document provides the details of this model.

CCS CONCEPTS

• **Computing methodologies** → **Maximum likelihood modeling**; **Mixture models**; **Latent variable models**; • **Information systems** → **Crowdsourcing**;

KEYWORDS

Crowdsourcing, label aggregation, maximum likelihood estimation, mixture models, probabilistic graphical models

1 THE MCMLI MODEL

We first present a novel probabilistic model for the MCMLI model. Then, we solve the model with an EM algorithm.

1.1 Label-Independent Model

We first propose a novel probabilistic generative model, namely *multi-class multi-label independent* (MCMLI) model, under an assumption that the labels are mutually independent. The probabilistic graphical model representation of MCMLI is illustrated in Figure 1.

Generation of true labels. For multi-class classification, each true label (supposed to be the mth label in multi-label annotation) is independently drawn from a multinoulli distribution with parameters $\boldsymbol{\theta}^{(m)} = [\theta_1^{(m)}, ..., \theta_K^{(m)}]$, where $\sum_{k=1}^{K} \theta_k^{(m)} = 1$. That is, for the mth label of an instance $\mathbf{x}_i$, we have $\mathrm{P}(y_i^{(m)} | \boldsymbol{\theta}^{(m)}) = \prod_{k=1}^{K} \left(\theta_k^{(m)}\right)^{\mathbb{I}(y_i^{(m)}=k)}$. Consequently, the probability of the M-dimensional true label vector $\mathbf{y}_i$ of the instance is

$$\mathrm{P}(\mathbf{y}_i | \Theta) = \prod_{m=1}^{M} \prod_{k=1}^{K} \left(\theta_k^{(m)}\right)^{\mathbb{I}(y_i^{(m)}=k)}, \tag{1}$$

where $\Theta = [\boldsymbol{\theta}^{(1)}, ..., \boldsymbol{\theta}^{(M)}]$ is a set of parameters for all M multinoulli distributions.

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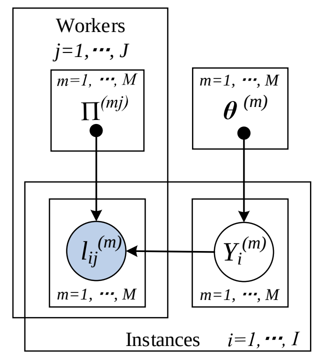

Figure 1: Probabilistic graphical model representation of the `MCMLI` model.

Generation of crowdsourced labels. In multi-class classification, a confusion matrix is a powerful tool that can comprehensively depict the distribution of a classifier's capability over all pairs of classes, providing fine-grained information to upper-layer applications. In MCMLI, each worker j independently provides value to each label of an instance $\mathbf{x}_i$. We use a set of confusion matrices $\mathbf{\Pi}^{(j)} = [\Pi^{(1j)}, ..., \Pi^{(Mj)}]$ to model the reliability of worker j with respect to M labels. We denote all sets of confusion matrices of totally J workers by a parameter set $\widetilde{\mathbf{\Pi}} = \{\mathbf{\Pi}^{(1)}, ..., \mathbf{\Pi}^{(J)}\}$. In matrix $\Pi^{(mj)}$, each element $\pi_{kd}^{(mj)} (1 \le k, d \le K)$ represents the probability of worker j labeling (true) class k as class d on the mth label, which derives $\mathrm{P}(l_{ij}^{(m)} = d | y_i^{(m)} = k) = \pi_{kd}^{(mj)}$. That is, $l_{ij}^{(m)}$ conditioning on $y_i^{(m)} = k$ obeys a multinoulli distribution with parameters $[\pi_{kd}^{(mj)}]_{d=1}^{K}$ and $\sum_{d=1}^{K} \pi_{kd}^{(mj)} = 1$.

Consider each instances $\mathbf{x}_i$ is independently labeled by J workers, the likelihood of all observed noisy labels on the instance can be calculated as follows:

$$\begin{aligned}\mathrm{P}\left(L_i | \widetilde{\mathbf{\Pi}}\right) = \sum_{k^{(1)}=1}^{k^{(1)}=K} \cdots \sum_{k^{(M)}=1}^{k^{(M)}=K} \Big[&\mathrm{P}\left(y_i^{(1)} = k^{(1)}, ..., y_i^{(M)} = k^{(M)} | \Theta\right) \\ &\cdot \mathrm{P}\left(L_i | y_i^{(1)} = k^{(1)}, ..., y_i^{(M)} = k^{(M)}, \widetilde{\mathbf{\Pi}}\right) \Big].\end{aligned} \tag{2}$$

Because we assume that the true labels of an instance are mutually independent, we have

$$\mathrm{P}\left(y_i^{(1)}=k^{(1)},...,y_i^{(M)}=k^{(M)}\middle|\Theta\right)=\theta_{k^{(1)}}^{(1)}\cdots\theta_{k^{(M)}}^{(M)},\quad(3)$$

$$\begin{aligned}&\mathrm{P}\left(L_i\middle|y_i^{(1)}=k^{(1)},...,y_i^{(M)}=k^{(M)},\widetilde{\mathbf{\Pi}}\right)\\&=\prod_{j=1}^{J}\mathrm{P}\left(l_{ij}^{(1)},...,l_{ij}^{(M)}\middle|y_i^{(1)}=k^{(1)},...,y_i^{(M)}=k^{(M)},\widetilde{\mathbf{\Pi}}\right)\\&=\prod_{j=1}^{J}\left(\prod_{m=1}^{M}\prod_{d^{(m)}=1}^{K}\left(\pi_{k^{(m)}d^{(m)}}^{(mj)}\right)^{\mathbb{I}(l_{ij}^{(m)}=d^{(m)})}\right).\end{aligned}\quad(4)$$

Here, because we need to present the prior of $\mathbf{y}_i$ under the conditions that each of its element is assigned with a different value, we use the superscript (m) to distinguish these ks on different labels. Similarly, the variable d is also decorated by the superscript (m).

Finally, the log-likelihood of all crowdsourced labels of the entire datasets is

$$\begin{aligned}\ln\mathrm{P}(\boldsymbol{L}|\Theta,\widetilde{\mathbf{\Pi}})=\sum_{i=1}^{I}\ln\Bigg(&\sum_{k^{(1)}=1}^{k^{(1)}=K}\cdots\sum_{k^{(M)}=1}^{k^{(M)}=K}\Big[\prod_{m=1}^{M}\theta_{k^{(m)}}^{(m)}\\&\cdot\prod_{j=1}^{J}\prod_{d^{(m)}=1}^{K}\left(\pi_{k^{(m)}d^{(m)}}^{(mj)}\right)^{\mathbb{I}(l_{ij}^{(m)}=d^{(m)})}\Big]\Bigg).\end{aligned}\quad(5)$$

1.2 Inference with EM

Our optimization objective is to maximize the likelihoods of the observed data $\mathbf{L}$ defined by Eq.(5), which can be achieved by expectation-maximization (EM) algorithm, which iteratively applies E-step and M-step.

E-step. We calculate the expected value of the log likelihood function, with respect to the conditional distribution of $\mathbf{Y}$ given the observed noisy labels $\mathbf{L}$ under the current estimates of parameters $\mathbf{\Psi}_1^{old}$:

$$\mathcal{Q}_1\left(\mathbf{\Psi}_1,\mathbf{\Psi}_1^{old}\right)=\mathbb{E}_{\mathbf{Y}|\mathbf{L},\mathbf{\Psi}_1^{old}}\left[\ln\mathrm{P}\left(\mathbf{L},\mathbf{Y}\middle|\mathbf{\Psi}_1\right)\right],\quad(6)$$

where $\mathbf{\Psi}_1=\{\Theta,\widetilde{\mathbf{\Pi}}\}$. In fact, this will simply result in the calculation of the joint posterior probability of $\mathbf{y}_i$ for each instance $\mathbf{x}_i$ by applying Bayes' theorem as follows:

$$\begin{aligned}&\mathrm{P}\left(y_i^{(1)}=k^{(1)},...,y_i^{(M)}=k^{(M)}\middle|\mathbf{L},\mathbf{\Psi}_1\right)\\&=\prod_{m=1}^{M}\mathrm{P}\left(y_i^{(m)}=k^{(m)}\middle|\mathbf{L},\mathbf{\Psi}_1\right)\\&\propto\prod_{m=1}^{M}\theta_{k^{(m)}}^{(m)}\prod_{j=1}^{J}\prod_{d^{(m)}=1}^{K}\left(\pi_{k^{(m)}d^{(m)}}^{(mj)}\right)^{\mathbb{I}\left(l_{ij}^{(m)}=d^{(m)}\right)}.\end{aligned}\quad(7)$$

Eq.(7) directly provides the expected value of an indicator function (calculated as a marginal probability) that will be used in M-step as follows:

$$\begin{aligned}\mathbb{E}\left[\mathbb{I}\left(y_i^{(m)}=k\right)\right]&=\mathrm{P}\left(y_i^{(m)}=k\right)\\&=\sum_{y_i^{(m')}(\forall m'\in\{1,...,M\}\backslash m)}\mathrm{P}\left(y_i^{(m)}=k,\cdots\middle|\mathbf{L},\mathbf{\Psi}_1\right)\end{aligned}\quad(8)$$

M-step. We determine the revised parameter estimate $\mathbf{\Psi}_1$ by maximizing the objective function $\mathcal{Q}_1$ formed as Eq.(6), i.e., $\mathbf{\Psi}_1^{new}=\mathrm{argmax}_{\mathbf{\Psi}_1}(\mathbf{\Psi}_1,\mathbf{\Psi}_1^{old})$. The parameters are updated as follows: (Derivation details are in Section 1.3.)

$$\hat{\theta}_k^{(m)}=\sum\nolimits_{i=1}^{I}\mathbb{E}\left[\mathbb{I}\left(y_i^{(m)}=k\right)\right]\Big/I,\quad(9)$$

$$\hat{\pi}_{kd}^{(mj)}=\frac{\sum_{i=1}^{I}\left\{\mathbb{E}\left[\mathbb{I}\left(y_i^{(m)}=k\right)\right]\mathbb{I}\left(l_{ij}^{(m)}=d\right)\right\}}{\sum_{i=1}^{I}\mathbb{E}\left[\mathbb{I}\left(y_i^{(m)}=k\right)\right]}.\quad(10)$$

After convergence. The integrated labels of instance $\mathbf{x}_i$ should be the sequence of class values with the maximum posterior probability. That is,

$$\hat{y}_i^{(1)},...,\hat{y}_i^{(M)}=\underset{k^{(1)},...,k^{(M)}}{\mathrm{argmax}}\left\{\mathrm{P}\left(y_i^{(1)}=k^{(1)},...,y_i^{(M)}=k^{(M)}\middle|\mathbf{L},\mathbf{\Psi}_1\right)\right\}.\quad(11)$$

1.3 Derivation Details in M-Step

M-step finds new values of the parameters that maximize the objective functions $\mathcal{Q}_1$ defined by Eq.(6). Because we have obtained the posterior probabilities of the latent variables, in the following derivations, we omit the condition of the observed label $\mathbf{L}$ and old values of parameters $\mathbf{\Psi}_1$.

For the MCMLI model, the objective is to maximize the quantity as follows:

$$\begin{aligned}\mathbb{E}_{\mathbf{Y}}\left[\ln\mathrm{P}\left(\mathbf{L},\mathbf{Y}|\mathbf{\Psi}_1\right)\right]&=\sum_{i=1}^{I}\mathbb{E}_{\mathbf{Y}}\left[\ln\mathrm{P}\left(\mathbf{l}_i,\mathbf{y}_i|\Theta,\mathbf{\Pi}_i\right)\right]\\&=\sum_{i=1}^{I}\mathbb{E}_{\mathbf{Y}}\left[\ln\left(\mathrm{P}\left(\mathbf{l}_i|\mathbf{y}_i,\mathbf{\Pi}_i\right)\underbrace{\mathrm{P}\left(\mathbf{y}_i|\Theta\right)}_{constant}\right)\right].\end{aligned}\quad(12)$$

We omit the constant factor with respect to the parameters $\mathbf{\Psi}_1$ in the partial derivatives. Thus, we only need to maximize the term $\sum_{i=1}^{I}\mathbb{E}_{\mathbf{Y}}\ln\mathrm{P}\left(\mathbf{l}_i|\mathbf{y}_i,\mathbf{\Pi}_i\right)$, which derives

$$\begin{aligned}&\sum_{i=1}^{I}\mathbb{E}_{\mathbf{Y}}\left[\ln\prod_{m=1}^{M}\prod_{k=1}^{K}\left(\theta_k^{(m)}\prod_{j=1}^{J}\prod_{d=1}^{K}\left(\pi_{kd}^{(mj)}\right)^{\mathbb{I}\left(l_{ij}^{(m)}=d\right)}\right)^{\mathbb{I}\left(y_i^{(m)}=k\right)}\right]\\&=\sum_{i=1}^{I}\sum_{m=1}^{M}\sum_{k=1}^{K}\mathbb{E}\left[\mathbb{I}\left(y_i^{(m)}=k\right)\right]\left[\ln\theta_k^{(m)}+\sum_{j=1}^{J}\sum_{d=1}^{K}\mathbb{I}\left(l_{ij}^{(m)}=d\right)\ln\pi_{kd}^{(mj)}\right].\end{aligned}\quad(13)$$

(1) Using a Lagrange multiplier to optimize Eq.(13) with respect to $\theta_k^{(m)}$, we construct a function

$$\mathcal{F}_1=\sum_{i=1}^{I}\mathbb{E}_{\mathbf{Y}}\ln\mathrm{P}\left(\mathbf{l}_i|\mathbf{y}_i,\mathbf{\Pi}_i\right)+\lambda\left(\sum_{k=1}^{K}\theta_k^{(m)}-1\right).\quad(14)$$

We let the partial derivative of Eq.(14) with respect to $\theta_k^{(m)}$ be zero. Applying sum-up-to-one condition $\left(\sum_{k=1}^{K} \theta_k^{(m)} = 1\right)$, we have

$$\frac{\partial \mathcal{F}_1}{\partial \theta_k^{(m)}} = \frac{\sum_{i=1}^{I} \mathbb{E}\left[\mathbb{I}\left(y_i^{(m)} = k\right)\right]}{\theta_k^{(m)}} + \lambda = 0 \tag{15}$$

$$\Rightarrow \sum_{k=1}^{K}\sum_{i=1}^{I} \mathbb{E}\left[\mathbb{I}\left(y_i^{(m)} = k\right)\right] = -\lambda \sum_{k=1}^{K} \theta_k^{(m)} \Rightarrow I = -\lambda. \tag{16}$$

Plugging Eq.(16) into Eq.(15), we have

$$\hat{\theta}_k^{(m)} = \sum\nolimits_{i=1}^{I} \mathbb{E}\left[\mathbb{I}\left(y_i^{(m)} = k\right)\right] \Big/ I.$$

(2) Using a Lagrange multiplier to optimize Eq(13) with respect to $\pi_{kd}^{(mj)}$, we construct a function

$$\mathcal{F}_2 = \sum_{i=1}^{I} \mathbb{E}_{\mathbf{Y}} \ln \mathrm{P}\left(\mathbf{l}_i \middle| \mathbf{y}_i, \mathbf{\Pi}_i\right) + \lambda \left(\sum_{k=1}^{K} \pi_{kd}^{(mj)} - 1\right). \tag{17}$$

We let the partial derivative of Eq.(17) with respect to $\pi_{kd}^{(mj)}$ be zero. Applying sum-up-to-one condition $\left(\sum_{d=1}^{K} \pi_{kd}^{(mj)} = 1\right)$, we have

$$\frac{\partial \mathcal{F}_2}{\partial \pi_{kd}^{(mj)}} = \frac{\sum_{i=1}^{I} \left\{\mathbb{E}\left[\mathbb{I}\left(y_i^{(m)} = k\right)\right] \mathbb{I}\left(l_{ij}^{(m)} = d\right)\right\}}{\pi_{kd}^{(mj)}} + \lambda = 0 \tag{18}$$

$$\Rightarrow \sum_{d=1}^{K}\sum_{i=1}^{I} \left\{\mathbb{E}\left[\mathbb{I}\left(y_i^{(m)} = k\right)\right] \mathbb{I}\left(l_{ij}^{(m)} = d\right)\right\} = -\lambda \sum_{d=1}^{K} \pi_{kd}^{(mj)}$$

$$\Rightarrow \sum_{i=1}^{I} \mathbb{E}\left[\mathbb{I}\left(y_i^{(m)} = k\right)\right] = -\lambda. \tag{19}$$

Plugging Eq.(19) into Eq.(18), we have

$$\hat{\pi}_{kd}^{(mj)} = \frac{\sum_{i=1}^{I} \left\{\mathbb{E}\left[\mathbb{I}\left(y_i^{(m)} = k\right)\right] \mathbb{I}\left(l_{ij}^{(m)} = d\right)\right\}}{\sum_{i=1}^{I} \mathbb{E}\left[\mathbb{I}\left(y_i^{(m)} = k\right)\right]}. \qquad \blacksquare$$