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Preface

This book includes the contributions presented at the 51st Scientific Meeting of the Italian Statistical Society (SIS) held in Caserta at the Università della Campania "Luigi Vanvitelli", from the 22nd to 24th of June, 2022.

The conference has registered more than 300 presentations, including 4 keynotes in plenary invited sessions and 9 presentations in 3 guest sessions, 48 presentations collected in 16 specialized sessions and 68 presentations in 17 solicited sessions, all dealing with specific themes in methodological and/or applied statistics and demography. Furthermore, more than 200 contributions, with one or more authors, have been spontaneously submitted to the Program Committee and arranged in 43 contributed sessions.

The high number of contributions and the large participation at the conference show that researchers have met the challenge of pursuing working even in the face of the pandemic period from which we are only now emerging. The research activity in our field therefore has never stopped, and the desire to participate in scientific events, as a place for exchange and discussion on new developments in our field, remains a living characteristic of our scientific community.

With the publication of this book, we wish to offer to all members of the Italian Statistical Society, all international academics, researchers, Ph.D. students, and all interested practitioners, a good snapshot of the on-going research in the statistical and demographic fields. We deeply thank all contributors for having submitted their works to the conference and all the researchers for their remarkable job in acting as referees accurately and timely. We also would like to thank the International Biometric Society (IBS) – Italian region, the European Network for Business and Industrial Statistics (ENBIS) and the Italian Society of Statistical Physics (SIFS) we had the pleasure of hosting. A special thanks is addressed to the Scientific and Organizational Committees for their great efforts devoted to all the organizational aspects, to the Università della Campania "Luigi Vanvitelli" and to the Department of Mathematics and Physics who made this event possible, as well as to the Municipality of the Town of Caserta who has patronized the event and to all the funders for their supports.

Finally, we wish to express our gratitude to the publisher Pearson Italia for all the support received.

Analyzing the Correlation Structure of Financial Markets Using a Quantile Graphical Model

Analisi della struttura di correlazione dei mercati finanziari usando un modello grafico quantile

Beatrice Foroni, Luca Merlo and Lea Petrella

Abstract In this paper we develop a quantile graphical model to identify the tail conditional correlation structure in multivariate data across different quantiles of the marginal distributions of the variables of interest. To implement the procedure, we consider the Multivariate Asymmetric Laplace distribution and exploit its location-scale mixture representation to build a penalized EM algorithm for estimating the sparse precision matrix of the distribution by means of an L_1 penalty. The empirical application is performed on a set of market indexes, cryptocurrencies and commodities.

Abstract *In questo articolo sviluppiamo un modello grafico quantile per identificare la struttura di correlazione condizionata di coda attraverso lo studio dei quantili delle distribuzioni marginali delle variabili di interesse. Per implementare la procedura, consideriamo la distribuzione di Laplace asimmetrica multivariata e sfruttiamo la sua rappresentazione a mistura per costruire un algoritmo EM penalizzato per la stima della matrice di precisione sparsa della distribuzione mediante una penalità* L_1*. La metodologia presentata viene applicata sui rendimenti finanziari dei principali indici di mercato, criptovalute e materie prime.*

Key words: EM Algorithm, Cryptocurrencies, Graphical Models, Multivariate Asymmetric Laplace Distribution

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1 Introduction

In recent years, the urge to identify how the impact of financial stress events can spread across the whole financial global system has made network science a useful tool for describing the propagation of systemic risk. Within this literature, Gaussian Graphical Models (GGM) have received an enormous attention because they provide a simple method to model the pair-wise conditional dependence structure of a collection of stochastic variables. In a high-dimensional framework, when a large set of random variables is considered, we are interested in identifying only a smaller subset of variables that exhibits the most relevant and strongest dependencies. Among the several methods proposed in literature, there is the *Graphical LASSO* (*glasso*) algorithm of [4], which maximizes the likelihood of the model penalized by the L_1-norm of the elements of the precision matrix. However, several empirical studies show that financial returns exhibit most of the well known stylized facts like fat tails, leptokurtosis and skewness, and deviation from normality makes it harder to characterize conditional dependence structures. The literature regarding non-Gaussian graphical models is fairly limited. In this context, the work of [3] provides a tool for robust model selection using multivariate t-distributions to model the data. Moreover, these proposals are not able to recover the dependencies in the tails of the distribution. Be able to understand and focus on specific part of a distribution such as the tails can really improve the knowledge in areas like financial contagion and systemic risk, where the dynamic of extreme events is of utmost importance. In this paper we develop a quantile graphical model to estimate the conditional tail correlation structure in multivariate data at different quantile levels of interest, without relying on the restrictive assumption of normally distributed data. In order to model the conditional correlation structure of multiple random variables at quantile-specific indices, we generalize the work of [7], which consider a reparametrization of the Multivariate Asymmetric Laplace (MAL) distribution of [6] to jointly model conditional quantiles of multiple random variables in a likelihood framework. Following [3], we demonstrate that the precision matrix of the MAL distribution completely characterizes the conditional dependence structure among the random variables at each quantile level, and allows us to construct a graph whose edges correspond to relations of conditional dependency. To induce sparsity in the precision matrix, we exploit the Gaussian location-scale mixture of the MAL and apply the *glasso* algorithm. In particular, following [5], we build a suitable Penalized EM (PEM) algorithm based on the maximization of the likelihood of the model penalized by the L_1-norm of the off-diagonal elements of the precision matrix. The estimated networks can be analyzed with respect to centrality measures as functions of the quantile level. The relevance of our approach is shown empirically among the cryptocurrency, commodity and stock market sectors from 2017 to 2021, and the modeling approach we propose is able to identify the connectedness as more serious levels of distress are considered, and can describe the topological structure of the underlying graph at different quantile levels of interest.

2 Model Specification

Given p quantile indexes $\tau = [\tau_1, \dots, \tau_p]'$, with $\tau_j \in (0,1)$, for $j = 1, \dots, p$, let $\mathbf{Y}_t = [Y_t^{(1)}, \dots, Y_t^{(p)}]$ denote a continuous p-dimensional random vector for $t = 1, \dots, T$. Generalizing the approach of [7], our objective is to develop a quantile graphical model for learning the conditional tail dependence structure among the components of $\mathbf{Y}_t$ at different quantile levels of interest τ. Specifically, we employ the MAL distribution, $\mathscr{MAL} \sim (\mu, \mathbf{D}\tilde{\xi}, \mathbf{D}\Sigma\mathbf{D})$, (see [6]) as:

$$f_{\mathbf{Y}}(\mathbf{y}_t) = \frac{2\exp\left\{(\mathbf{y}_t - \mu)'\mathbf{D}^{-1}\Sigma^{-1}\tilde{\xi}\right\}}{(2\pi)^{p/2}|\mathbf{D}\Sigma\mathbf{D}|^{1/2}} \left(\frac{\tilde{m}_t}{2+\tilde{d}}\right)^{\nu/2} K_\nu\left(\sqrt{(2+\tilde{d})\tilde{m}_t}\right), \tag{1}$$

where μ is the location parameter, $\mathbf{D}\xi \in \mathscr{R}^p$ is the scale (or skew) parameter, with $\mathbf{D} = \text{diag}[\delta_1, \delta_2, \dots, \delta_p]$, $\delta_j > 0$ and $\xi = [\xi_1, \xi_2, \dots, \xi_p]'$, having generic element $\xi_j = \frac{1-2\tau_j}{\tau_j(1-\tau_j)}$. Σ is a $p \times p$ positive definite matrix such that $\Sigma = \Lambda\Psi\Lambda$, with Ψ being a correlation matrix and $\Lambda = \text{diag}[\sigma_1, \sigma_1, \dots, \sigma_p]$, with $\sigma_j^2 = \frac{2}{\tau_j(1-\tau_j)}$, $j = 1, \dots, p$. Finally, $\tilde{m}_t = (\mathbf{y}_t - \mu)'(\mathbf{D}\Sigma\mathbf{D})^{-1}(\mathbf{y}_t - \mu)$, $\tilde{d} = \tilde{\xi}'\Sigma^{-1}\tilde{\xi}$, and $K_\nu(\cdot)$ denotes the modified Bessel function of the third kind with index parameter $\nu = (2-p)/2$. One of the key benefits of the MAL distribution is that, using (1) and following [6], the $\mathscr{MAL} \sim (\mu, \mathbf{D}\tilde{\xi}, \mathbf{D}\Sigma\mathbf{D})$ admits the following location-scale mixture representation:

$$\mathbf{Y} = \mu + \mathbf{D}\tilde{\xi}W + \sqrt{W}\mathbf{D}\Sigma^{1/2}\mathbf{Z} \tag{2}$$

where $\mathbf{Z} \sim \mathscr{N}_p(\mathbf{0}_p, \mathbf{I}_p)$ denotes a p-variate Normal distribution and $W \sim \text{Exp}(1)$ has a standard Exponential distribution, with $\mathbf{Z}$ being independent of W. Hence, the mixture representation in (2) represents the generating process of a MAL random vector $\mathbf{Y}$ from a latent Gaussian random vector $\mathbf{Z}$ with correlation matrix Ψ and a single latent Exponential variable with mean 1. In particular, the constraints imposed on $\tilde{\xi}$ and Λ represent necessary conditions for model identifiability for any fixed quantile level $\tau_1, \dots, \tau_p$ and guarantee that $\mu^{(j)}$ is the τ_j-th quantile of $Y_t^{(j)}$, for

$j = 1, \dots, p$.

To build the graphical model, let $G = (V, E)$ be an undirected graph where $V = \{1, \dots, p\}$ is the set of nodes, such that each component of the random variable $\mathbf{Y}_t$ corresponds to a node in V, and $E \subseteq V \times V$ represents the set of undirected edges. In order to study the conditional dependence structure of $\mathbf{Y}_t$ through the graph G, we exploit the MAL representation in (2). For notational convenience and to illustrate the similarities with the GGM, we define the precision matrix $\mathbf{K} = \Psi^{-1}$. Following the *t*-distribution graphical model approach in [3], we establish the following proposition.

Proposition 1. *For a fixed p-dimensional vector of quantile levels* $\tau = [\tau_1, \tau_2, \dots, \tau_p]'$ *such that* $\tau_j \in (0,1)$*, for* $j = 1, \dots, p$*, let* $\mathbf{Y} \sim \mathscr{MAL}(\mu, \mathbf{D}\xi, \mathbf{D}\Lambda\mathbf{K}^{-1}\Lambda\mathbf{D})$*. If two nodes j and k, with* $j, k \in V$ *and* $j \neq k$*, of the graph are separated by a set of nodes* $C \in V$*, then* $\mathbf{Y}^{(j)}$ *and* $\mathbf{Y}^{(k)}$ *are conditionally uncorrelated given* $\mathbf{Y}^{(C)}$.

The proof of Proposition 1 follows directly from the mixture representation of the MAL in (2) and the closure property of the Normal distribution under conditioning of its components. Most importantly, from Proposition 1 follows that the zero entries in the precision matrix $\mathbf{K}$ imply the conditional uncorrelation between the components of $\mathbf{Y}_t$ at each given quantile level τ. To estimate and make inference on the model parameters we develop a suitable Expectation-Maximization (EM) algorithm, which exploits the mixture representation of the MAL distribution, treating W as missing data. In order to identify only a smaller subset of variables that exhibit the most relevant and strongest dependencies, we construct a PEM algorithm by adding an L_1-norm penalty of the off-diagonal elements of $\mathbf{K}$ to the likelihood of the model. Specifically, for a given vector $\tau = [\tau_1, \tau_2, \dots, \tau_p]'$, the penalized complete log-likelihood function is proportional to:

$$\ell_c(\Phi_\tau) \propto \frac{T}{2} \log|\mathbf{D}^{-1}\mathbf{K}\mathbf{D}^{-1}| - \frac{T}{2} \mathrm{tr}\{\mathbf{K}\mathbf{S}\} - \rho||\mathbf{K}||_1 \tag{3}$$

with

$$\mathbf{S} = \frac{1}{T} \sum_{t=1}^{T} \frac{1}{W_t} \Lambda^{-1}\mathbf{D}^{-1}(\mathbf{Y}_t - \mu - \mathbf{D}\xi W_t)(\mathbf{Y}_t - \mu - \mathbf{D}\xi W_t)'\mathbf{D}^{-1}\Lambda^{-1} \tag{4}$$

and where W_t is an Exponential random variable with mean 1.

As it can be noticed, the likelihood function in (3) is convex in $\mathbf{K}$. Therefore, at each iteration of the PEM, this feature allows us to adopt the *glasso* algorithm for efficient estimation of the sparse precision matrix $\mathbf{K}$.

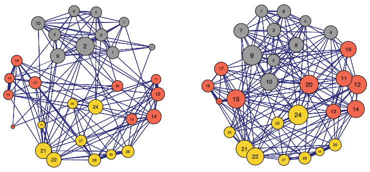

Fig. 1 Graphs for $\tau = 0.50$ (left) and $\tau = 0.95$ (right). Yellow, grey and red nodes represent respectively indexes, cryptocurrencies and commodities while the vertex labels are illustrated in Table 1.

3 Main Results and Conclusions

The empirical analysis is performed using the R software on the log-returns of 29 financial assets comprising stock market indices, commodity futures and digital currencies from September 14, 2017 and to June 21, 2021. We set $\tau = \tau_j$, $j = 1,\dots,29$, and fit the proposed model for a sequence of 99 quantile levels $\tau = [0.01, 0.02, \dots, 0.98, 0.99]'$. Then, for each τ, we construct the corresponding graph G_τ.

Sectors					
Cryptos		Commodities		Stock Index	
1: Bitcoin	**6: Litecoin**	**11: Gold**	**16: Brent**	**21: S&P 500**	**26: Dax**
2: Ethereum	**7: Binance Coin**	**12: Silver**	**17: Gasoline**	**22: Dow Jones**	**27: Ftse Mib**
3: Ripple	**8: Eos**	**13: Palladium**	**18: Heating oil**	**23: Nasdaq**	**28: Cac**
4: Tether	**9: Stellar**	**14: Platinum**	**19: Natural Gas**	**24: Shangai composite index**	**29: Euro Stoxx50**
5: Bitcoin Cash	**10: Tron**	**15: Crude Oil**	**20: Ethanol**	**25: Nikkei 225**	

Table 1 Financial sectors considered in the analysis. Numbers identify vertex labels in Figure 1.

In Figure 1 we represent the estimated graph at $\tau = 0.50$ and $\tau = 0.95$ to show how the density of the network changes between tranquil ($\widehat{G}_{0.50}$) and bullish periods ($\widehat{G}_{0.95}$), respectively. The size of the node is proportional to the degree centrality and the width of the edges is determined by the magnitude of the estimated correlations in $\widehat{K}$. A deeper analysis to describe how the interconnectedness and contagion risk change as a function of the quantile index τ, is conducted by showing in Figure 2 the edge density (left) and the modularity measure (right) as functions of τ. The edge density shows a highly interconnected system, even for the smallest ratio of value at the center of the distribution. It is evident a strongest dependency during bearish and bullish periods, as the edge density is the largest in the tails.The presence of community structures is summarized in the modularity measure plot of Figure 2.
Consistently with the estimated graph $\widehat{G}_{0.50}$ in Figure 1, during tranquil periods the reduced number of connections brings out heterogeneity in the distribution of

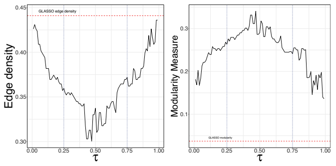

Fig. 2 From left to right, Edge density and Modularity measure as a function of τ. Blue dotted lines identify the 25th and 75th percentiles to mark respectively crisis and bullish markets periods. Red dotted line identify the centrality measure associated with the *glasso*.

edges, i.e., high concentration of edges within groups of nodes and low concentrations between groups. This behavior can be explained by the so-called co-explosion of cryptoassets already discussed by [1],which evidences that price explosivity in one cryptocurrency can lead to explosivity in other cryptocurrencies. In conclusion, with our approach we are able to recover valuable information at each quantile level even without the assumption of normality. The whole analysis conveys a highly connected network which becomes even more dense during bearish and bullish markets periods, and the results are in line with existing studies ([2, 1]). With this model we strengthen the existing literature in this field, implementing a technique to adjust the *glasso* algorithm to a quantile structure of dependence.

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