

# Exponential Random Graph Models with Big Networks: Maximum Pseudolikelihood Estimation and the Parametric Bootstrap

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**Abstract**—With the growth of interest in network data across fields, the Exponential Random Graph Model (ERGM) has emerged as the leading approach to the statistical analysis of network data. ERGM parameter estimation requires the approximation of an intractable normalizing constant. Simulation methods represent the state-of-the-art approach to approximating the normalizing constant, leading to estimation by Monte Carlo maximum likelihood (MCMLE). MCMLE is accurate when a large sample of networks is used to approximate the normalizing constant. However, MCMLE is computationally expensive, and may be prohibitively so if the size of the network is on the order of 1,000 nodes (i.e., one million potential ties) or greater. When the network is large, one option is maximum pseudolikelihood estimation (MPLE). The standard MPLE is simple and fast, but generally underestimates standard errors. We show that a resampling method—the parametric bootstrap—results in accurate coverage probabilities for confidence intervals. We find that bootstrapped MPLE can be run in 1/10th the time of MCMLE. We study the relative performance of MCMLE and MPLE with simulation studies, and illustrate the two different approaches by applying them to a network of bills introduced in the United States Senate.

**Index Terms**—network, ERGM, parametric bootstrap, maximum pseudolikelihood

## I. INTRODUCTION

The field of network science faces a double-edge sword when it comes to computationally intensive research. First, the availability of digital source data has led the growth in network science to be synonymous with the growth in research on big data. Faraj et al. (2008, pp. 19–20) [8] notes that,

“In recent years the proliferation of advanced Information Technology has not only facilitated the collection of large-scale network data but also increased the availability of large-scale network data analysis tools and techniques. This has led to an explosion of interest in large network research in fields spanning biology, physics, mathematics, and social sciences.”

Second, analytical methods are growing more sophisticated, increasingly involving iterative and/or simulation-based optimization, rather than simple descriptive calculations [33]. Closing the gap in terms of the size of the networks to which it

is feasible to apply the most sophisticated methods of network modeling requires research into scalable methods of inference. We propose a method of statistical inference for one of the most popular models for networks—the exponential random graph model (ERGM), in which both parameter estimates and confidence intervals are derived, that can require less than half the compute time of currently used methods.

## II. THE EXPONENTIAL RANDOM GRAPH MODEL

The ERGM is a probabilistic model for networks [4], [25], [37]. They can be used for link prediction [21], simulating network adjacency matrices [12], and testing theories regarding the processes underlying tie formation [11]. The ERGM was first introduced by Holland and Leinhardt (1981) [13]. However, due to the intractable normalizing constant in the likelihood function of the ERGM, it did not see widespread and complete use until the 2000s, following the development of algorithms and software for efficient simulation-based methods for working with ERGM [32]. Training ERGM using simulation-based methods is computationally expensive, and can still be prohibitively burdensome with data on big networks. Approximate methods of estimation, which are much more feasible with large networks, have existed for some time, but these methods perform poorly when it comes to characterizing the uncertainty in parameter estimates, which is necessary when assessing risk in predictions or simulation, or in hypothesis testing.

The ERGM takes the adjacency matrix of an observed network  $G^{obs}$ , which is a matrix-valued random variable. This means that a network of  $N$  nodes can be defined as an adjacency matrix  $G = (g_{ij}) \in [\mathcal{K}, \mathcal{K}]^{N \times N}$ , where  $g_{ij} \in \{0, 1\}$  for all  $i, j \in \{1, \dots, N\}$ .  $g_{ij} = 1$  means that there is an edge between actors  $i$  and  $j$ , while  $g_{ij} = 0$  indicates that these actors are not directly connected. Since the model does not consider loops, one has  $g_{ii} = 0$  for all  $i \in \{1, \dots, N\}$ . Furthermore, define

$$\mathcal{G}(N) := \left\{ G \in \mathbb{R}^{(N \times N)} : g_{ij} \in \{0, 1\}, g_{ii} = 0 \right\}$$

as the set of all possible networks on  $N$  nodes without loops. Note that the cardinality of set  $\mathcal{G}(N)$  is increasing

exponentially for every newly included actor, which results in  $2^{N(N-1)/2}$  total elements. For even a small number of nodes, the cardinality of  $\mathcal{G}(N)$  turns out to be an astronomically large number. For this reason calculating the likelihood function of the ERGM, which requires evaluating a normalizing constant on  $\mathcal{G}(N)$  is either extremely time-consuming or with today's technology not achievable. As a consequence, many approximation methods have been provided by the literature, with the most popular method making use of Markov Chain Monte Carlo (MCMC) methods [16], as we will introduce in the next section.

The probability function for the ERGM is defined as

$$\mathbb{P}_\theta(G) = \frac{\exp(\theta^T \cdot \Gamma(G))}{\sum_{G^* \in \mathcal{G}(N)} \exp(\theta^T \cdot \Gamma(G^*))} \quad (1)$$

where  $\theta \in \mathbb{R}^q$  is a  $q$ -dimensional vector of parameters,  $\Gamma : \mathcal{G}(N) \rightarrow \mathbb{R}^q$ ,  $G \mapsto (\Gamma_1(G), \dots, \Gamma_q(G))^T$  is a  $q$ -dimensional function of different network statistics and  $c(\theta) := \sum_{G^* \in \mathcal{G}(N)} \exp(\theta^T \cdot \Gamma(G^*))$  is a normalization constant which ensures that (1) defines a probability function on  $\mathcal{G}$ . As already mentioned, a specific network  $G$  can be considered as a manifestation of a matrix-like random variable, whose probability of occurrence can be modeled with equation (1). The generative processes captured by a model (e.g., density, reciprocity, popularity, clustering) are informed by the decision regarding which network statistics (i.e.,  $\Gamma(\cdot)$ ) are incorporated (see Snijders et al. (2006) [31] for a detailed discussion). The flexibility of the ERGM in capturing virtually any network generative process has led to it being applied broadly across several fields, including (but not limited to) sociology [29], [34], economics [20], political science [5], [18], ecology [3], [7], and neuroscience [27], [28].

### III. ESTIMATION

As mentioned above calculating  $c(\theta)$  is not achievable for most cases with today's technology. Straightforward application of either maximum likelihood estimation and Bayesian inference are, therefore, not possible. The first method proposed in the literature for estimating ERGM parameters was maximum pseudolikelihood estimation [35]. Under maximum pseudolikelihood, the joint distribution is replaced by the product over conditional distributions [2].

$$\mathbb{P}_\theta(G) \approx \prod_{ij} \mathbb{P}_\theta(g_{ij} | G_{-ij}),$$

where  $G_{-ij}$  is the adjacency matrix, excluding element  $ij$ .

This corresponds with the *logistic regression* approach, where the observations of the dependent variables are simply edge values of the observed adjacency matrix, and the observations of the covariate values are given as the scores of every single change statistic. Therefore, the estimation of  $\theta$  can then be obtained as usual using straight forward maximum-

likelihood estimation. The resulting likelihood function is of the following form:

$$\text{lik}(\theta) = \mathbb{P}_\theta(Y = G) = \prod_{i,j} \frac{\exp(\theta^T \Delta(G)_{ij})}{1 + \exp(\theta^T \Delta(G)_{ij})} \quad (2)$$

The problem with this simple estimation procedure is that the assumed hypothesis of the independence of the dyads turns out to be erroneous in many cases (see van Duijn et al. [36]). This is a systematic problem: The presence of network data is inextricably connected with the presence of *relational data*, which by definition should not be assumed to be independent of each other. If this dependency structure is deliberately ignored and equation (2) is used to estimate  $\theta$ , it results in a *maximum pseudo-likelihood estimation* (MPLE). This technique tends to underestimate the standard error. However, Desmarais and Cranmer [6] argue that the pseudo-likelihood provides a consistent approximation of the maximum likelihood, meaning that the MPLE converges to the MLE as the size of the network increases.

There are several techniques to circumvent estimators, which underestimate the standard error of  $\theta$ . In the following, we will introduce a technique based on *Markov Chain Monte Carlo* (MCMC) and maximum-likelihood methods.

The more rigorous technique is to estimate the parameters directly with the log-likelihood function derived from (1), which has the following form:

$$\text{loglik}(\theta) = \theta^T \cdot \Gamma(G) - \log(c(\theta)) \quad (3)$$

where  $G$  is the observed network. For the vector of network statistics, one can assume without loss of generality

$$\Gamma(G) = 0 \quad (4)$$

This means that centering the vector of network statistics does not affect the probability function of the network variable  $Y$ . Therefore, in context of the likelihood function (3) the vector of statistics can always be assumed to be centered on the observed network.

Due to assumption (4), one gets from (3) the simplified log-likelihood function

$$\text{loglik}(\theta) = -\log(c(\theta)) \quad (5)$$

The problem resulting from estimating the parameters with (3) is that the term

$$c(\theta) := \sum_{G^* \in \mathcal{G}(N_V)} \exp(\theta^T \cdot \Gamma(G^*))$$

which sums up the weighted network statistics of all possible networks of  $N$  nodes, has to be evaluated. Even for networks with small numbers of nodes this presents an enormous computational obstacle, and the necessary calculations for larger networks cannot currently be completed in any reasonable timeframe. As a result, for sufficiently large networks it is not possible to estimate the parameters directly with the likelihood function.

An expedient for this limitation is based on the following consideration: Fix any vector of parameters  $\theta_0 \in \Theta$  from the underlying parameter range  $\Theta$  and compute for  $\theta \in \Theta$  the expected value. Then, one can show that

$$\mathbb{E}_{\theta_0} [\exp((\theta - \theta_0)^T \cdot \Gamma(Y))] = \frac{c(\theta)}{c(\theta_0)}$$

This equation offers the following possibility: If one draws  $L$  random networks  $G_1, \dots, G_L$  out of a distribution  $\mathbb{P}_{\theta_0}$  appropriately, one gets with the *law of big numbers* the following relation:

$$\begin{aligned} \frac{1}{L} \cdot \sum_{i=1}^L \exp((\theta - \theta_0)^T \cdot \Gamma(G_i)) &\xrightarrow{\mathbb{P}_{\theta_0}} \\ \mathbb{E}_{\theta_0} [\exp((\theta - \theta_0)^T \cdot \Gamma(Y))] &= \frac{c(\theta)}{c(\theta_0)} \end{aligned} \quad (6)$$

For a big enough number,  $L$ , of random networks, the following approximation is reasonable:

$$\frac{c(\theta)}{c(\theta_0)} \approx \frac{1}{L} \cdot \sum_{i=1}^L \exp((\theta - \theta_0)^T \cdot \Gamma(G_i)) \quad (7)$$

One can now use equation (7) to determine an approximation of the log-likelihood function (5):

$$\begin{aligned} &\log \text{lik}(\theta) - \log \text{lik}(\theta_0) \\ &= -\log(c(\theta)) + \log(c(\theta_0)) \\ &= -\log\left(\frac{c(\theta)}{c(\theta_0)}\right) \\ &= -\log(\mathbb{E}_{\theta_0} [\exp((\theta - \theta_0)^T \cdot \Gamma(Y))]) \\ &\approx -\log\left(\frac{1}{L} \cdot \sum_{i=1}^L \exp((\theta - \theta_0)^T \cdot \Gamma(G_i))\right) \end{aligned}$$

By differentiating this equation on both sides with respect to  $\theta$  one gets an approximate score function:

$$s(\theta) \approx -\frac{\partial}{\partial \theta} \log\left(\frac{1}{L} \cdot \sum_{i=1}^L \exp((\theta - \theta_0)^T \cdot \Gamma(G_i))\right) \quad (8)$$

This approximate score function now can be used as usual, i.e., it can be iteratively approximately optimized with the *Newton-Raphson algorithm* or by *Fisher scoring*. As a result, the approximate maximum-likelihood estimator for the parameters can be computed.

As pleasant as this may sound, the immediate question arises: How can a sufficient number of suitable drawings  $G_1, \dots, G_L$  be taken from the distribution  $\mathbb{P}_{\theta_0}$ ?

For this purpose, the *Markov Chain Monte Carlo (MCMC)* methods can be used. This approach does not deliberately ignore the dependency structures inside the network. Furthermore, the Markov Chain Monte Carlo Maximum Likelihood Estimator (MCMLE) approaches the MLE as the number of networks simulated to approximate the likelihood goes to infinity.

No matter which kind of MCMC algorithm is used, the basic

idea is the following:

One constructs a *Markov chain*  $(G_t)_{t \in \mathbb{N}}$  on the set of all possible networks  $\mathcal{G}(N)$  of  $N$  nodes, whose *stationary distribution* is in conformity with the distribution  $\mathbb{P}_{\theta_0}$ . One can show that every single realization (or *trajectory*) of this stochastic process accomplishes the convergence result (6) (for this version of the *Law of big numbers for Markov chains* we reference Meyn and Tweedie [22]). As a result, sub-sequences of  $(G_t)_{t \in \mathbb{N}}$  which are sufficiently large enough can be used for approximation (7).

Snijders [30] provides a Metropolis Hastings algorithm on how to simulate networks: Choose a matrix  $G^{(0)} \in \mathcal{G}(N)$  to start with (e.g., the observed network). For  $k \in \{0, \dots, L-1\}$  recursively proceed as follows:

- 1) Randomly choose an edge  $(i, j)$  where  $i \neq j$  from  $G^{(k)}$
- 2) Compute the value

$$\pi := \frac{\mathbb{P}_{\theta}(Y_{ij} \neq g_{ij}^{(k)} | Y_{ij}^c = G_{ij}^c)}{\mathbb{P}_{\theta}(Y_{ij} = g_{ij}^{(k)} | Y_{ij}^c = G_{ij}^c)}$$

- 3) Fix  $\delta := \min\{1, \pi\}$  and draw a random number  $Z$  from  $\text{Bin}(1, \delta)$ . If

- $Z = 0$ , let  $G^{(k+1)} := G^{(k)}$
- $Z = 1$ , define  $G^{(k+1)}$  via

$$g_{pq}^{(k+1)} = \begin{cases} 1 - g_{pq}^{(k)} & \text{if } (p, q) = (i, j) \\ g_{pq}^{(k)} & \text{if } (p, q) \neq (i, j) \end{cases}$$

- 4) Start at step 1 with  $G^{(k+1)}$ .

The depicted algorithm provides a sequence of random networks  $G_0, \dots, G_L$ . Since the original matrix was chosen randomly and the first simulated networks are very dependent on the chosen matrix (only one edge is changed per iteration), usually the first  $B$  networks, where  $N \ll B \ll L$ , are discarded as the so called Burn-In.

#### IV. EFFICIENCY OF MPLE AND MCMLE

Even though the MCMLE is in general favored over the MPLE there are also cases where the MPLE comes in handy. Foremost, MPLE is quick and simple, since estimation can be done by basic logistic regression and does not exert elaborate MCMC methods. As mentioned in the previous chapter the MPLE approaches the MLE as the size of the networks increase and as a consequence, is a consistent estimator (see Lindsay [19], Strauss and Ikeda [35], Hyvarinen [17], Desmarais and Cranmer [6]). This implies that for an increasing number of nodes the MPLE converges in probability to the MLE, meaning that for large enough networks the MPLE becomes an option to computationally intensive MCMC methods.

At this point we want to mention that we are familiar with the work of Shalizi and Rinaldo [26], arguing that consistency is not given in the ERGM framework. They prove that one cannot

run an ERGM on a sub-network in order to make inferences about the full network. The way we use the term *consistency* in this paper is different and aligns with the way consistency is defined by Lindsay [19], i.e. instead of considering sub-networks that converge to the full size network, we argue that both, the MLE as well as the MPLE, approach the true coefficient values as the size of networks generally increases.

Next, we are going to compare the efficiency of the MCMLE compared to the MPLE. Desmarais and Cranmer [6] show the MPLE outperforms the MCMLE if the number of simulated networks used to approximate the likelihood is not chosen large enough. It is even more remarkable that the number of simulated networks needed for the MCMLE, in order to surpass the MPLE increases as the size of the network increases. This means that for very large networks it becomes difficult to determine the number of simulated networks required in order for the MCMLE to outperform the MPLE. In other words, the larger the network of interest is, the larger one has to choose the number of simulated networks in order to justify the time intensive MCMLE approach.

To demonstrate this disadvantage of the MCMLE we conduct a simulation study using Goodreau’s Faux Mesa High School data, which represents a simulation of an in-school friendship network among 203 students as well as the Faux Magnolia High School data, representing an in-school friendship network among 1451 students. The data for both networks originates from Resnick et al. [23].

For both networks we first calculate the MCMLE and treat the estimated coefficients as the network’s true values  $\theta$ . Then, we take the same parametrization, using the number of edges, the nodal attribute for gender and the geometrically weighted edgewise shared partners (gwesp) distribution (see Hunter [15]) where we fix the decay parameter  $\lambda$  at 0.25. The number of edges in these undirected networks are defined as

$$\Gamma_{edges} : \mathcal{G}(N) \rightarrow \mathbb{R} \quad , \quad G \mapsto \sum_{i < j}^N g_{ij}$$

In order to include nodal covariates into the ERGM, the vector of nodal attributes is expanded into an artificial matrix  $C$ , which has the same dimensions as  $G$ . The first row of matrix  $C$  consists of the first actor’s attribute, repeated  $N$  times. The second row of matrix  $C$ , consists of the second actor’s attribute, repeated  $N$  times, and so on. Then, the statistics for a nodal covariate is defined as

$$\Gamma_{nodal} : \mathcal{G}(N) \rightarrow \mathbb{R} \quad , \quad G \mapsto \sum_{i < j}^N g_{ij} c_{ij}$$

A precise description of the gwesp statistic will be given in the chapter VI.

We simulate  $m = 500$  new networks using the ‘true’ coefficients and estimate the MPLE as well as the MCMLE of these simulated networks. For every single simulated network the

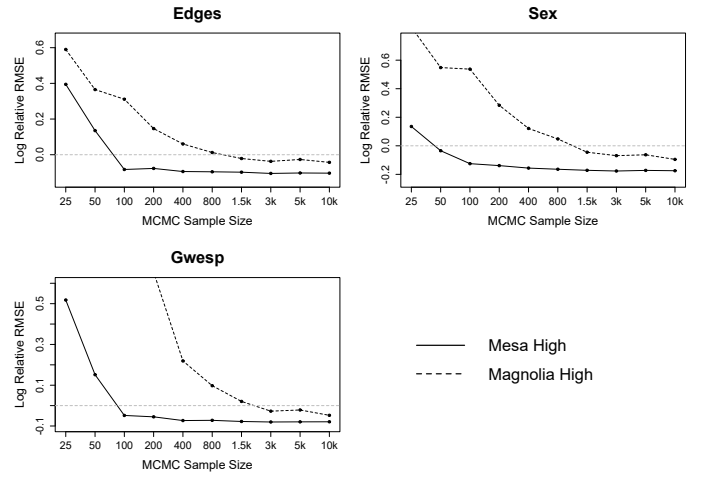


Fig. 1. The log of the ratio of the RMSE for the MCMLE to the MPLE for different sample sizes and two different networks, Faux Mesa High and Faux Magnolia High

MCMLE calculation is being repeated several times for 25 to 10,000 simulated networks used in the likelihood approximation. Based on these results, we compute the root mean square error, which is a measure of the accuracy of an estimator, combining both, the bias and the variance. Mathematically written, the RMSE for an estimator  $\hat{\theta}$  is defined as

$$RMSE = \sqrt{\sum_{i=1}^m (\theta - \hat{\theta}_i)^2}$$

implying that the smaller the RMSE, the more accurate is the estimator. Since the MCMLE has higher efficiency and converges to the MLE, the RMSE decreases as the number of simulated networks used for the likelihood approximation increases. On the other hand, the RMSE of the MPLE is a constant value since no network simulations are required. In order to compare the RMSE of the two estimation techniques, we take the log of the ratio of the MCMLE to the MPLE. As a result, a negative value indicates a better MCMLE performance, while a positive value indicates a better MPLE performance.

Figure 1 visualizes the results of the simulation study. The solid line illustrates the results of the log relative RMSE of the Faux Mesa High network, while the dashed line illustrates the corresponding results of the Faux Magnolia High network. The plots support the fact that larger networks require a larger sample size of simulated networks for the MCMLE to outperform the MPLE. While the fairly small Faux Mesa High network only requires a sample size of about 50–100 networks the larger Faux Magnolia High network already requires a sample size of at least 1500 networks for the MCMLE to surpass the MPLE. These results propose especially for very large networks (e.g. social media data) the question, of how large the sample size has to be set in order to justify the approximately exact, but computationally expensive MCMLE

method. The identification of the required sample size is not only becoming more difficult as the size of the network increases, but an increase of the sample size will also extend the mere computation time.

## V. BOOTSTRAPPED MPLE

As discussed in the previous section, the MPLE converges to the MLE as the size of the network increases. Moreover, the MPLE is able to outperform the MCMLE if the sample size is not chosen large enough. The main reason why the MCMLE is still widely preferred is that in contrast to the MPLE, it does not underestimate the standard deviation (van Duijn et al. [36]). By the definition of the ERGM it is obvious that this model is an exponential family distribution where  $\theta$  is the natural parameter and  $\Gamma(Y)$  is the sufficient statistic. For exponential family distributions it is known that the sampling distribution of the MLE is multivariate normal with mean vector equal to the MLE and a covariance matrix equal to the inverse of the negative Hessian matrix  $[-H]^{-1}$  of the likelihood function at the MLE. The problem with the MPLE is that calculating  $[-H]^{-1}$  by the pseudolikelihood function will underestimate the variance of the MPLE [36], resulting in an underestimate of the width of the confidence intervals. van Duijn et al. show that constructing 95% MPLE confidence intervals can result in intervals that comprise the true value in less than 75% instead of the demanded 95%. In this paper, we are going to refer to the MPLE confidence intervals as *logistic regression confidence intervals* simply because the MPLE is calculated using logistic regression methods that also use the inverse of the negative Hessian matrix as an estimate for the covariance matrix.

Since the MPLE has the advantage of being approximately exact and computationally inexpensive, but has the disadvantage of underestimating corresponding confidence intervals, we apply a technique referred to as *bootstrapped MPLE*, that was first introduced by Desmarais and Cranmer [6] and provides a consistent estimate of MPLE confidence intervals. Desmarais and Cranmer argue that this bootstrapped MPLE is a multivariate  $M$ -estimator (see Huber [14]), a special class of robust estimators, meaning that this algorithm consistently estimates the confidence intervals of the MPLE.

We verify the consistency of the bootstrapped MPLE by conducting a simulation study on the same two networks with the same parametrization as in the previous chapter: The Faux Mesa High friendship network and the Faux Magnolia High friendship network. For the simulation study, we determine the MPLE for the model and treat these estimates as the networks' 'true' parameter values. We then use these parameter values to simulate a sample of 1000 networks from the distribution of  $Y$ . For each of the 1000 networks, we calculate 95% confidence intervals based on the MCMLE and the logistic regression and examine whether the 'true' parameter values lie in these intervals. In addition, we determine the bootstrapped MPLE confidence intervals by sampling 500 networks for each of

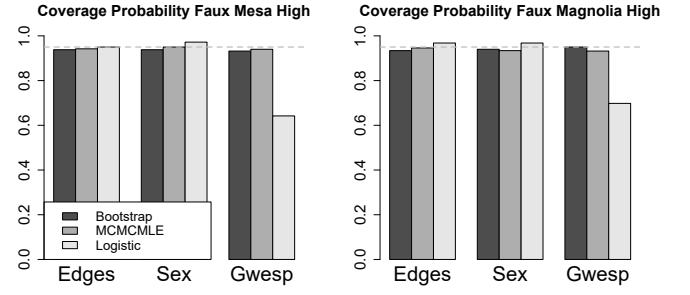


Fig. 2. The Coverage Probability results of the Faux Mesa High network (left) and of the Faux Magnolia High network (right) for bootstrapped MPLE, MCMLE and logistic regression

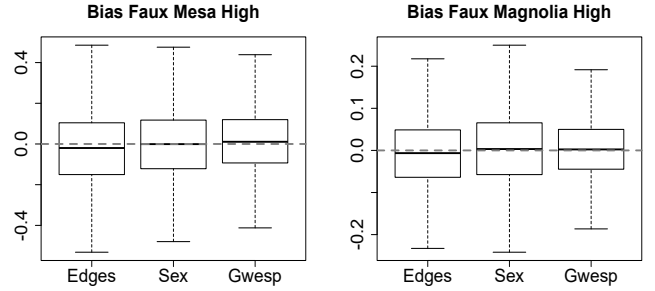


Fig. 3. The boxplots visualize the bias ( $\hat{\theta} - \theta$ ) over the 500 iterations for the Faux Mesa High network (left) and the Faux Magnolia High network (right)

the originally sampled 1000 networks, by using the respective MPLE as parameter values. For every newly sampled network, we again determine the MPLE and then take the 2.5th and 97.5th percentile of the 500 MPLE estimates to obtain a 95% bootstrap confidence intervals. Similar as for the MCMLE and the logistic regression, we verify whether the 'true' parameter value can be found in the bootstrapped confidence interval.

Figure 2 visualizes the coverage percentages for each of the three methods for both networks. The dashed line is set at 0.95 and represents the optimal value. It is evident that the bootstrapped MPLE performed equally well as the MCMLE, achieving results that obtain the true parameter values in approximately 95% of the cases. Additionally, a difference in the results between the smaller Faux Mesa High network and larger Faux Magnolia High network is not identifiable. Similar to the results of van Duijn et al. [36] our results for the logistic regression differ distinctively from the anticipated 95%, visualizing that the MPLE underestimates the variance of its estimates. Figure 3 illustrates the bias between the 'true' network coefficients  $\theta$  and the MPLE estimates. We can abstract from this figure that the median MPLE estimates concur with the networks' 'true' coefficients. It is especially worthwhile to mention that the bias of the larger Faux Magnolia High network is smaller than the bias of the Faux Mesa High network, supporting the fact that the MPLE converges to the MLE as the network size increases.

This simulation study shows that bootstrapped MPLE is able to overcome the main disadvantage of the MPLE by retaining the validity of confidence intervals. Furthermore, this method also adopts the advantage of the MPLE of being consistent. However, the main advantage of the bootstrapped MPLE is the rapidity of the estimation that provides a computational benefit, especially if the size of the examined network is extremely large.

## VI. COSPONSORSHIP NETWORK DATA

To illustrate the performance of MCMLE relative to that of the bootstrapped MPLE we apply both approaches to the data on cosponsorship of bills in the U.S. House of Representatives for the 108th Congress (2003–2004), developed by Fowler (2006) [9] [10]. The cosponsorship network consists of 2,635 nodes, which we define as pieces of legislation (i.e., bills), considered by the Senate during the 108th Congress. Note that this formulation of the cosponsorship network differs from past research, which has defined the nodes as the individual legislators. Because there are more bills than legislators, studying bills as nodes provides a more disaggregated look at the network than is offered through studying the network of legislators. In this undirected network bills are tied together based on the similarity of the sets of legislators who cosponsor them. Specifically, we include an edge between bills  $i$  and  $j$  if the correlation coefficient between the indicator vectors indicating whether  $i$  and  $j$  were sponsored each legislator is greater than a random uniform draw. This results in an undirected network with [CHRISTIAN, HOW MANY?] edges.

We build an ERGM specification that extends the work of Zhang et al. (2008) [38] in exploring the structure of cosponsorship ties. They find that congressional cosponsorship is primarily characterized by intra-party ties—among Republicans and among Democrats, but few cross-party ties. We test for this party-based clustering (i.e., homophily) in our ERGM. This is done through a term that accounts for the party of senators. The party homophily term is defined as

$$h(G, X) = \sum_{i < j} G_{ij} X_{ij},$$

where  $G$  is the network adjacency matrix, and  $X$  is an indicator matrix that assumes the value 0 if  $i$  and  $j$  were sponsored by legislators from different political parties and 1 if they were sponsored by legislators from the same party.  $h(G, X)$  measures the number of intra-party ties in the network. A positive parameter value for this statistic indicates that ties tend to be formed between bills sponsored by the same political party.

We extend the homophily-based model to account for a network dynamic that is commonly found in the study of networks—that of popularity or preferential attachment [1]. Preferential attachment is the tendency for new ties to be formed with nodes who already have many ties (i.e., popular nodes). The alternating  $k$ -star statistic was introduced by Snijders et al. [31] and modified by Hunter and Handcock (2006) [15]. A positive parameter estimate associated with the

alternating  $k$ -star statistic indicates that tie formation follows a form of preferential attachment [31]. The alternating  $k$ -star statistic adds one network statistic to the model equal to a weighted alternating sequence of  $k$ -star statistics with weight parameter  $\lambda$  and is a way to include a network's entire degree distribution as a network statistic. In this model we fix the weight parameter  $\lambda = 0.4975$ . Snijders et al. [31] introduced an approach involving  $k$ -star statistics  $S_1(G), \dots, S_{N-1}(G)$ , where  $S_k(G)$  denotes the number of  $k$ -stars in the network,  $k \in \{1, \dots, N-1\}$ . For simplicity, let us define

$$S_k(G) := \Gamma_{star(k)}(G)$$

where

$$\Gamma_{star(k)} : \mathcal{G}(N) \rightarrow \mathbb{R} \quad , \quad G \mapsto \sum_{i,j,k} g_{ij} g_{ik}$$

Note that in every network  $S_1(G) = \Gamma_{edges}(G)$ , i.e.,  $S_1(G)$  is equal to the number of edges in the network. On this basis, Snijders introduces the *alternating  $k$ -star statistics*

$$\begin{aligned} \mathfrak{S}(G, \lambda) &:= \sum_{k=2}^{N-1} \left(-\frac{1}{\lambda}\right)^{k-2} S_k(G) \\ &= S_2(G) - \frac{S_3(G)}{\lambda} + \dots + (-1)^{N-3} \frac{S_{N-1}(G)}{\lambda^{N-3}} \end{aligned}$$

Models with this statistic and a fixed decay parameter turn out to be standard ERGMs and Hunter and Handcock [15] succeeded in proving that one can also rewrite alternating  $k$ -stars as a function of a network's degree distribution

$$\mathfrak{S}(G, \lambda) = \lambda \left( \lambda \sum_{j=1}^{N-1} \left(1 - \left(1 - \frac{1}{\lambda}\right)^j\right) D_j(G) + 2S_1(G) \right) \quad (9)$$

where  $D_j(G) := \Gamma_{deg(j)}(G)$  is the number of nodes with a degree of  $j$ . In the next step, we define the *geometrically weighted degree* (gwd) statistic as the first summand of (9)

$$\Gamma_{gwd}(G, \lambda) := \lambda \sum_{j=1}^{N-1} \left(1 - \left(1 - \frac{1}{\lambda}\right)^j\right) D_j(G) \quad (10)$$

At this point it also becomes obvious where the *geometrically* comes from. It simply refers to the geometric sequence  $(1 - \frac{1}{\lambda})^j$  which appears in these statistics.

In a very similar way we can also define gwesp, as applied in chapter IV, as

$$\Gamma_{gwesp}(G, \lambda) := \lambda \sum_{j=1}^{N-1} \left(1 - \left(1 - \frac{1}{\lambda}\right)^j\right) \Gamma_{esp(k)}(G)$$

where

$$\Gamma_{esp} : \mathcal{G}(N) \rightarrow \mathbb{R} \quad , \quad G \mapsto \sum_{i < j} \mathbf{1}_k \left( \sum_{k=1}^N g_{ij} g_{im} g_{jm} \right)$$

This means this statistic counts the number of nodal pairs  $(i, j)$ , which share exactly  $k$  neighbors.

As nodal attribute we implement the partisanship of the bill

	MCMLE		Logistic Regression		bootstrapped MPLE	
	Estimate	St. Error	Estimate	St. Error	Lower Bound	Upper Bound
Edges	-5.884	0.065	-5.869	0.015	-6.007	-5.751
Sponsor Party	1.440	0.015	1.440	0.015	1.411	1.467
Alternating k-star	0.124	0.064	0.108	0.006	-0.011	0.2379

TABLE I

ESTIMATION RESULTS FOR THE COSPONSORSHIP NETWORK USING MCMLE, LOGISTIC REGRESSION AND BOOTSTRAPPED MPLE

sponsor.

We estimate the coefficient of this matrix using both techniques, the MCMLE and the bootstrapped MPLE. The MCMLE requires a sample size of at least 1000 networks to converge. The bootstrapped MPLE was estimated by using 500 simulated networks. As we described in the chapter *Estimation*, only one edge at a time is changed when simulating networks. For better comparison, we chose the same Burn-In (300.000 MH-steps) and the same number of iterations (30.000 MH-steps) for sampling networks. The results can be found in table VI.

It is interesting to see that the standard error calculated by the logistic regression approach is constantly smaller than the standard error of the MCMLE, which leads to inaccurate confidence intervals as shown in figure 2. Furthermore, we can observe that the coefficients for the number of edges and the nodal attribute are very similar, but the estimates for the alternating k-star statistic do differ (*REASON FOR altkstar?*). The bootstrapped MPLE bounds, however, include each estimate for both methods.

The bootstrapped MPLE is not only simple and fast, it is also embarrassingly parallel, meaning that there is no problem separating the computation into several tasks. In other words, by using multiple cores, the computing time for estimating bootstrapped MPLE confidence intervals can be reduced substantially. Figure 4 illustrates the relative computing time of the bootstrapped MPLE using 500 simulated networks and the MCMLE for the three networks Faux Mesa High (205 nodes), Faux Magnolia High (1461 nodes) and Cosponsorship (2635 nodes) for an increasing number of computing cores. For the small network we simulate 2000 networks using a MCMC interval of 2000 steps, for the medium network we simulate 8000 networks using a MCMC interval of 5000 steps and for the large network we simulate 10000 networks using 30,000 MCMC steps in order to approximate the likelihood appropriately. The chosen sample sizes and MCMC steps are necessary to guarantee a good model fit. We define the simulation time of the bootstrapped MPLE as a function of the number of available computing cores  $x$ :

$$\text{bootstrapped MPLE time} = \text{network simulation time} + \frac{500 \cdot \text{MPLE estimation time}}{x}$$

Based on this, we define the relative computing time as

$$\text{relative computing time} = \frac{\text{bootstrapped MPLE time}}{\text{MCMLE time}}$$

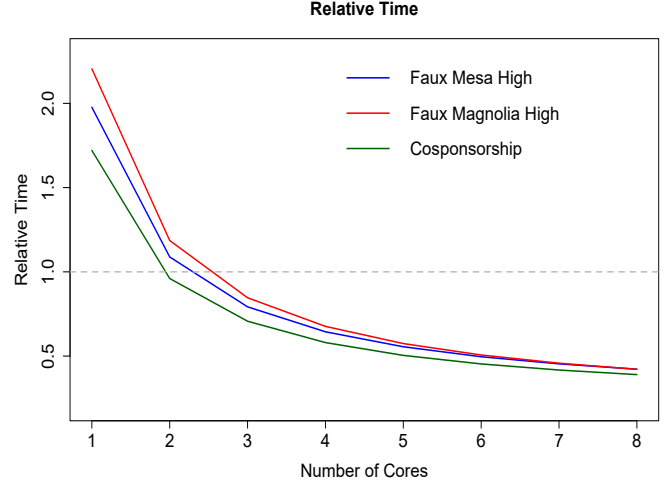


Fig. 4. The y-axis gives the ratio of the bootstrapped MPLE time to that of the MCMLE time. Values below 1 indicate that the bootstrapped MPLE requires a shorter computing time.

This means that a relative computing time greater than 1 indicates that the MCMLE computing time is shorter, while a relative computing time smaller than 1 indicates that the bootstrapped MPLE provides faster results.

Figure 4 demonstrates that all three networks only require three cores for the bootstrapped MPLE to outperform the computing time of the MCMLE and that the computing time can further be reduced if more computing cores are available. If more computing cores are being used the ratio of the bootstrapped MPLE time to the MCMLE time levels off at about 0.2, meaning that the computing time can be quintupled using the bootstrapped MPLE. This figure also depicts that larger networks in general require a longer computation time and will benefit more if the bootstrapped MPLE is used.

Of course the actual computing time for a network always depends on the statistics that are included in the network, but in general larger networks require longer computation times, since a larger MCMC sample size is required and more MC steps are necessary to simulate a new network that does not overly depend on the previous sample. This makes the bootstrapped MPLE a beneficial alternative especially for very large networks.

One of the major disadvantages of MPLE over MCMLE is that it cannot assess *degeneracy*. When fitting an ERGM one



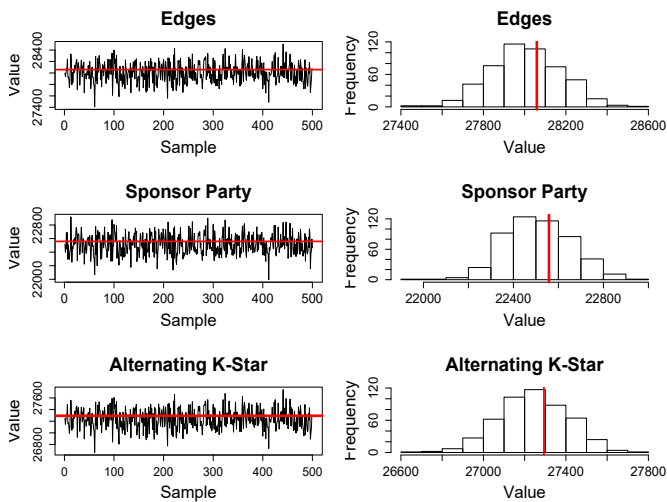


Fig. 5. Network statistics of the 500 bootstrap samples for the cosponsorship network. The thick line in both, the traceplots and the histograms, represents the network statistics of the observed network.

usually has to deal with the problem of unreliable approximately likelihood estimates for the model's parameters. The reason why degeneracy occurs is that the stochastic process generated by the MCMC-algorithm does not necessarily hold through the model's defined distribution of the random variable  $Y$  as stationary distribution (see Handcock [?] and Rinaldo et al. [24]). The bootstrapped MPLE, however, allows assessing degenerate models as well. In order to verify whether a model is degenerate or not, one can take a look at density and trace plots as visualized in figure 5. The trace plots on the left side depict the attained values via MCMC simulated networks for every single statistic included into the model, centered on the statistic values of the observed network. The plots on the right side visualize the empirical density function of the respective statistic, based on the simulated networks (Hunter and Handcock [15]). For a non-degenerated model the empirical density function should be approximately symmetrical around zero for every included centered statistic, since this corresponds with the expected value of a centered statistic (compare equation (4)). Otherwise, the values of the simulated networks systematically differ from the corresponding statistics in the observed network, making it unreasonable to assume that the simulated networks originate from the same distribution as the observed network. Furthermore, the trajectories in the trace plot should not indicate a dependence structure. This would be a signal that the constructed stochastic process violates the Markov properties.

## VII. CONCLUSION

In the past years the ERGM grew in popularity in many different fields and with this popularity also the size of the considered networks rose. As the size of the network increases, it becomes unclear how many simulated networks are necessary for the conventional MCMLE method in order to provide reliable results. Furthermore, as an increasing number

of simulated networks is necessary for the MCMLE, the computing time rapidly goes sky high. For this reason it is essential to develop different methods that provide faster estimation than the MCMLE, but still lead to reliable results. In this paper we introduced the bootstrapped MPLE as an alternative estimation method for ERGMs and compared the performance to the commonly applied MCMLE. Based on a simulation study we first pointed out that the larger the size of a network is the larger the MCMC sample size has to be chosen in order for the MCMLE to outperform the fast and simple MPLE. However, the big disadvantage of the MPLE is that even though it is an approximately exact estimator, it underestimates the standard error. For this reason, we propose a parametric bootstrap method to attune the standard error. On the basis of another simulation study on two different networks we demonstrate that the bootstrapped MPLE covers the true coefficients just as well as the MCMLE, while the simple MPLE performs clearly poorer. This means that the bootstrapped MPLE combines the advantages of both methods, the MPLE and the MCMLE, because it is still simple, fast and provides approximately exact results, but also does not underestimate the standard error. We conclude that the bootstrapped MPLE should be regarded as a propitious alternative to the MCMLE. It also has the advantage of being embarrassingly parallel, which leads to a rapid speed-up of the calculation if multiple computing cores are used.

## VIII. ACKNOWLEDGEMENTS

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