

Predicting the 2014 Ebola Outbreak in West Africa using Network Analysis

Milestone Report

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Abstract

The current Ebola outbreak in West Africa is the worst in history. Most traditional epidemiological models are compartmental models that have a random-mixing assumption. These models calculate the effective reproductive rate of an outbreak. We survey three of these models: the classic SIR (Susceptible, Infectious, Recovered) model and two extensions used in Ebola research.

Network models allow for avoiding the random-mixing assumption inherent in compartmental models. This is done by assigning each individual a finite set of permanent contacts. We review generated contact network models for SARS, including an urban network, a random network, and a scale-free network. We then review a worldwide network model that represents traffic flowing across transportation networks and consider approaches for predicting the extent of an Ebola outbreak.

I. INTRODUCTION

TODO: Add introduction

II. RELATED WORK

Related work by (Gomes et al., 2014) attempts to predict the spread of Ebola to different parts of the world based on a model that incorporates both the compartmental approach and the use of world-wide air traffic flows.

In (Meyers et al., 2005), the authors model the spread of the 2002-2003 outbreak of SARS in Hong Kong and Canada using a contact network. A contact network model attempts to characterize every interpersonal contact that can potentially lead to disease transmission in the community, with each person in the community represented as a node and each contact represented as an edge between them.

The majority of research in epidemiological theory is based on the compartmental model, which is not a network model. In order to simply capture the dynamics of disease spread over time, the compartmental model employs a population-wide random mixing assumption, meaning that each individual has a small and equal chance of coming into contact with any other individual in the population. To model the progress of an epidemic in a large population, the individuals in the population are compartmentalized according to the state of the disease. The most widely used such model is the SIR model introduced in (Kermack and McKendrick, 1932):

- **Susceptible (S):** Individuals who have not yet caught the disease from contact with an infectious individual.
- **Infectious (I):** Individuals who have the disease. They have some probability of infecting susceptible people.
- **Recovered (R):** Individuals who have experienced the full infectious period, and are now non-infectious and immune.

The changes among these states over time are represented by a set of differential equations. The basic reproductive number R_0 is defined as the average number of secondary cases generated by a primary case in a pool of mostly susceptible individuals, and is an estimate of epidemic growth at the start of an outbreak if everyone is susceptible.

In (Chowell et al., 2004), the authors model the effect of Ebola outbreaks in 1995 in Congo and in 2000 in Uganda using a compartmental model similar to the SIR model. However, a distinct feature of Ebola is that individuals exposed to the virus who become infectious do so after a mean incubation period. In order to reflect this feature, the SIR model is extended with an additional “Exposed” compartment state. This SEIR model is summarized in Figure 1:



Fig. 1: SEIR model

In (Legrand et al., 2007), the Ebola outbreaks in Congo in 1995 and Uganda in 2000 are also studied. However, a major difference from (Chowell et al., 2004) is that (Legrand et al., 2007) models the spreading of disease in heterogeneous settings.

In order to gain better insight of the epidemic dynamics, the infectious phase is subdivided into three stages: infection in a community setting (I), infection in a hospital setting (H), and infection after death assuming a traditional funeral (F).

This SEIHFR compartmental model is summarized in Figure 2.

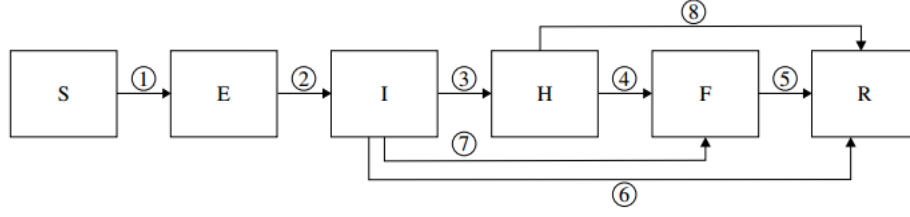


Fig. 2: SEIHFR model

For our purposes, as described below, we stopped short of implementing this complicated model.

III. MODELING LOCALIZED EPIDEMIC SPREAD

Estimating model parameters and basic reproduction number for 2014 Ebola data using a random mixing model

In first phase of the project, to calculate the basic reproduction number of the current Ebola epidemic spread at different countries, we performed model fitting on the data we gathered from Rivers (2014). We considered the SEIR model described in Chowell et al. (2004). The SEIR model under consideration is a non-linear model with six parameters. The current Ebola epidemic is still spreading and depending on the preventative measures taken, the underlying dynamics of the spread can change drastically anytime. We fitted our model to three countries in the West Africa - Guinea, Sierra Leone and Liberia. In addition, we performed model fitting for the West Africa Region by adding up the data from these three countries. Given the limited number of data available, instead of fitting all six parameters to the model, we decided to fix some of the parameters based on the studies on previous Ebola epidemic. In Chowell et al. (2004), the incubation time of the Ebola $1/k$ is found to be varying between 1 to 21 days, with a mean time of 6.3 days for previous Ebola spread. For ease of data fitting, we set this parameter value to the mean value of 6.3 days. We note that, the dynamics of the current epidemic may differ from previous one, and therefore fixing a value based on the prior estimate may lead to some inaccuracy. To model the effect the intervention on the spread of the epidemic, a modified transmission rate β_1 is generally used instead of the initial transmission rate β_0 at later stage of the epidemic. The transition of β_0 to β_1 depends on intervention time τ and decaying factor q . The choice of intervention time is a very difficult problem. To this end, we looked into different sources like Wikipedia, WHO and CDC website to learn more about the timeline of the spread. In Guinea, a 2-year-old boy fell in December 2, 2013, later diagnosed as Ebola patient. We consider this incidence as the index case for Guinea and set t_0 to December 2. In March 2, the Government of Guinea informed WHO regarding the possibility of Ebola epidemic and declared national health emergency. We considered this date as the intervention date and set τ to 110. In Sierra Leone, one person fell in April 2014. In June 12, 2014 the country declared emergency and closed borders with neighboring Guinea and Liberia. We consider the first date as t_0 and second date as intervention time, therefore set τ to 50. In Liberia, in March 31, 2014, there were official confirmation of two person getting infected from Ebola. We set this date to t_0 and set I_0 and C_0 in our model as 2. The Government of Liberia shut down all schools in July 30, 2014. We consider this date as the date of intervention and set τ to 120.

In order to fit the non-linear SEIR model to data, we used non-linear least square estimation. We use the reported data (t_i, c_i) for $i = 1, 2, \dots, n$ where t_i denote the i -th reporting time and c_i as the cumulative number of infectious cases from the beginning of outbreak time t_0 to time t_i . The optimization problem contains a large number of local minimas. Therefore, the choice of initial parameter estimate is an important consideration to get the global optimum solution. In order to find a good initial choice of the parameters as an input to the non-linear least square solver, we first perform a Latin hypercube sampling on the 4-dimensional parameter space. We grid up the hypercube with a number of grid points in each dimension. We then choose the sample that minimizes the least square error as the initial input. In order to calculate the 95% confidence interval of estimated parameter, we performed bootstrapping based on residual error.

The estimated parameters for the SEIR model of Guinea, Sierra Leone, Liberia, as well as West Africa region is presented in the appendix. In Figure 3, we presented the the number of incidence at different compartments of the SEIR model, as well as the cumulative number of infectious cases over time. Our model fit was based on the last data we collected in October 21, 2014. As of today, November 11, 2014, few additional data points are available; we also plotted those data points in the graph. In addition to that, we extrapolated the graph up to December 31, 2014. We note that, the forecasting to future cases may not be appropriate as the underlying factors of the Epidemic are changing rapidly with the increase in safety measures. We observe that, the prediction of the model to the cases up to November 11 is mostly in par with the observed data for Guinea and Sierra Leone. We note that, for Guinea epidemic, we have data for the longest range of days as the initial case was in December 2. The estimated model, therefore, captures most of the dynamics of the spread in Guinea in contrast to

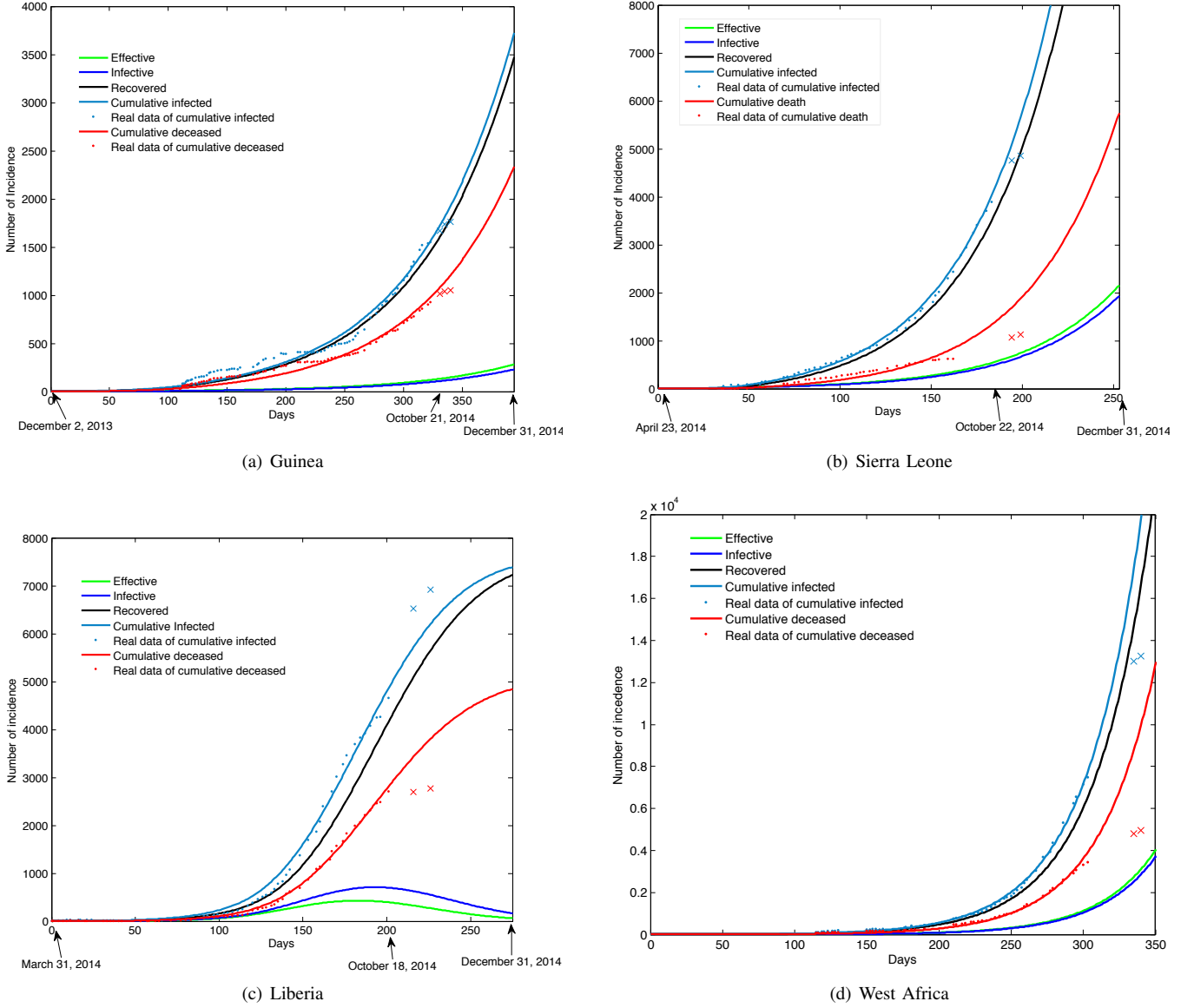


Fig. 3: SEIR model fit results for 2014 Ebola epidemic data

the other cases. In case of Liberia, our prediction under-estimated the observed data. Our guess is the estimated parameters for Liberia may be overfitting the model. While performing some exploratory analysis on the Liberia data, we observed some discrepancies, e.g. decrease in cumulative value from the previous data points, which may somewhat distorted the model fitting parameters. For the West Africa region plot, our prediction number is much higher than the actual data. This is understandable, as the underlying assumption behind SEIR model is random mixing. Within a country without any movement restriction, this model is somewhat appropriate. However, for the aggregated model among multiple countries, this assumption is no longer valid due to stricter movement regulations between country borders. Therefore a model with random mixing assumption will over predict the infectious number of cases.

As an extension of the above approach, to find parameters for the model based on the current data, we designed and ran the simulation using mcmc approach with input as time series data for the various infected regions. Initial values for the various parameters were assumed as above for the prior distribution but the range based on the literature was used to find the most appropriate values for the current outbreak. For example β_0 had a range $[0,1]$, β_1 had a range $[0,1]$, infection time $(1/\gamma)$ had range $[3.5,10.7]$, incubation time $(1/k)$ had a range $[5, 22]$ and (τ) had a range $[100,150]$. The simulation is currently running on a server and we will have results in the final report.

Planned network-based modeling approaches

TODO: We are looking at modeling via $G(n, m)$ and contact networks.

IV. PREDICTING WORLDWIDE SPREAD

Approach

In order to predict how the Ebola epidemic might spread across the world, we have assembled a worldwide network based on international trade. Because the trade numbers are in US dollars, we have assumed a linear relationship between exports in dollars and travelers going abroad. This is a strong assumption, and we are currently exploring various options for utilizing the international trade network for this purpose.

Data Preparation

The trade network dataset we are using is based on data retrieved from the web service API to the UN Comtrade database (United Nations, 2014) via their web service API. The data queried for were country-to-country SITC-1 exports from the latest data available for each country.

Several problems with this raw dataset immediately became apparent which required working around. Many war-torn countries such as Liberia have not reported detailed export data to the UN in decades (Liberia last reported in 1984). As a result of this, the export totals are incorrect for the present day. In addition, this old data reports exports to countries that no longer exist, including East Germany and Yugoslavia. In order to make the dataset usable for modern-day predictions, we performed the following transformations on the data (using Perl scripts):

- Manually remapped non-existent countries to their modern equivalents. In some cases, we had to do a best-effort mapping. For example, Yugoslavia split into many states, so we remapped exports to Yugoslavia to exports to modern-day Slovakia, since Slovakia currently has the largest economy of the states that once comprised Yugoslavia.
- Removed exports from states that no longer exist, preferring export data from modern equivalents.

In order to get something as close as we believe possible to modern-day export data, we then needed to make the per-country exports sum up to the latest available export data. The United States Central Intelligence Agency (2013) publishes a World Factbook that contains up-to-date export totals for most countries in the world. We downloaded the above data set and, on the (admittedly strong) assumption that the export distribution from country-to-country in the UN Comtrade data set has remained the same between the last year a country has reported detailed export data and the latest totals from the CIA, we linearly renormalized each outgoing edge in our data set so that the total sum of exports equalled the latest CIA data. This also required a manual step of mapping country names in the UN data set to the names used in the CIA data set (due to abbreviations, alternate names such as Myanmar vs. Burma, etc).

Finally, once we had a “renormalized” data set including detailed export edges and totals matching the latest available data, we needed to map these numbers to theoretical international travelers. We could not find any publicly available data on the number of international outgoing travelers per country (although these numbers are available for a subset of countries from disparate sources, such as the US department of travel). Only total air travellers are available, which includes domestic flights. Our current approach to do this mapping is to assume a linear relationship between imports to a country and international travelers to that country per year.

It has currently not proven possible to find reliable data for number of outbound travelers per country per year, especially for Ebola-affected countries. Lacking this, we have had to come up with some heuristic to determine how to map dollars exported to travelers. One such approximation is using the United States as a model, and using the ratio of imports to the United States to the number of tourists visiting the United States in a year. Based on data from the US Office of Travel & Tourism Industries (2013), 69.77 million people visited the United States in 2013. According to our renormalized data set, total imports into the United States were \$2.21 trillion during that same period. Dividing imports by visitors, an admittedly simplistic measure, gives us a scaling factor of approx. 31,665. Therefore we have applied this scaling factor to all edges in our network, giving us some approximation of outbound travellers from country to country.

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APPENDIX

TABLE I: Parameter estimation for Ebola SEIR model (Guinea & Sierra Leone)

Incidence Dependent Parameters	Guinea			Sierra Leone		
	Value	Comments		Value	Comments	
Initial Case t_0	December 2, 2013	one person fell ill		April 23, 2014	one person fell ill	
S_0	0	-		0	-	
E_0	0	-		0	-	
I_0	1	-		1	-	
R_0	0	-		0	-	
C_0	1	-		1	-	
Intervention time	March 2, 2014	Gov. of Guinea informed WHO		June 12, 2014	Country declared emergency	
τ	110	-		50	-	
Estimated Parameters	Value	95% CI	Comments	Value	95% CI	Comments
Incubation Time $1/k$	6.3	-	based on previous works	6.3	-	based on previous works
Infection Time $1/\gamma$	5.4957	[5.43, 5.545]	-	6.36	[6.324, 6.396]	-
β_0	0.2407	[0.2374, 0.244]	-	0.357	[0.3525, 0.3613]	-
β_1	0.2084	[0.2033, 0.2135]	-	0.2012	[0.1994, 0.2028]	-
q	32	[0.1, 100]	-	34	[1.9, 110]	-
Fatality Rate	0.67	-	-	0.38	-	-
R_0	1.323	[1.295, 1.341]	-	2.27	[2.243, 2.298]	-
R_1	1.145	-	-	1.28	-	-

TABLE II: Parameter estimation for Ebola SEIR model (Liberia & West Africa overall)

Incidence Dependent Parameters	Liberia			West Africa		
	Value	Comments		Value	Comments	
Initial Case t_0	March 31, 2014	official confirmation two infected		December 2, 2013	one person fell ill in Guinea	
S_0	0	-		0	-	
E_0	0	-		0	-	
I_0	2	-		1	-	
R_0	0	-		0	-	
C_0	2	-		1	-	
Intervention time	July 30, 2014	School shutdown		March 2, 2014	Gov. of Guinea informed WHO	
τ	120	-		110	-	
Estimated Parameters	Value	95% CI	Comments	Value	95% CI	Comments
Incubation Time $1/k$	6.3	-	based on previous works	6.3	-	based on previous works
Infection Time $1/\gamma$	10.7	[8.9, 10.7]	-	6.8	-	-
β_0	0.169	[0.168, 0.191]	-	0.2	-	-
β_1	0.0001	[0.0001, 0.1]	-	0	-	-
q	0.0085	[0.0072-0.0264]	-	0	-	-
Fatality Rate	0.67	-	-	-	-	-
R_0	1.808	-	-	1.36	-	-
R_1	0.001	-	-	-	-	-