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Virus Spread Modeling and Simulation: A Behavioral Parameters Approach and Its Application to Covid-19

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Abstract: How a virus spread on a network is a really important topic and even more important is to classify the danger of a virus. With this goal in mind, we investigate the characteristics that define the most deadly virus. Moreover, we aim to provide a simplified discrete-time simulation, described by few parameters, as a straightforward alternative to more complex models of diseases diffusion. The simulation is used to model the spread of the infection, and the obtained results are then analyzed to understand how the virus' behavior varies by changing its characteristics and the network topology.

1 INTRODUCTION

Urbanization and the destruction of natural habitats are creating the perfect conditions for new diseases. This problem will be increasingly frequent, as explained by Dodds (Dodds, 2019), especially due to close contact with wildlife and livestock. Moreover, if new diseases originates it is not easy to find a cure. Thus, understanding how a disease spreads is the key for prevention.

This has become clear in the last decades, from the HIV epidemic to Ebola and, finally, with Covid-19.

Research is not only beneficial to alleviate the workload for the health system but to improve the overall quality of life of the population even during a crisis, reducing the loss of human life and the long-term effects that some diseases have on the patients' body.

In this paper, a new approach is taken for simulating a new virus, to find what makes a virus effective and what might help its spread. The two characteristics that are analyzed are: network topology and the dead rate and diffusion rate of the virus.

2 LITERATURE REVIEW

With the outbreak of coronavirus 2 (SARS-CoV-2), many studies have been carried out to try understanding the virus impact on the modern highly connected society (e.g. (Alassafi et al., 2022; Li and Yan, 2022; Hasaninasab and Khansari, 2022; Yadav and Vishwakarma, 2022; Ronaghi et al., 2022)). In the state-of-the-art literature of epidemiological researches, the SIR model is a widely used tool to predict the evolution of infection diseases. For example, the SIQR model, a variant of SIR model, introduces a new state Q (Quarantine) for the individuals, and it achieves a better health outcome for mass testing with respect to the SIR model (Harckbart, 2020). The model SEIR, instead, introduces a new class E for the exposed individuals who are not infectious yet, and it has been employed, for example, to assess the effectiveness of the policies, adopted in several Italian regions, and their impact on future scenarios (Godio et al., 2020). Another alternative is the SEIQR model, which includes both new states for the individuals for a more complex and complete prediction. This last model can be applied also to curb the impact of the transmission of malicious objects in a highly connected computer network (Mishra and Singh, 2011).

An alternative to the SIR models adopted in the literature is proposed in (Kurtin et al., 2020). Here,

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the authors proposes a stochastic model to simulate person-to-person contact, represented as circles bouncing in a 2D plane getting in contact with each other.

The SIR model, with its variants, is mostly employed to simulate virus propagation and to predict possible contagion scenarios, starting from data collected on an already existing disease. In this work, rather than predicting the virus outbreak or evaluating the effectiveness of the measures to contain the infection, the virus is modeled in such a way that its parameters are tuned to maximize the harmfulness of the virus itself, the infection and the subsequent possible death. Once the optimal parameters are discovered, different scenarios are considered by either changing the virus' parameters or varying the network characteristics, and their impact on the virus' infection is analyzed. Several analogies with the SIR model emerges throughout the analysis of the conducted work; however, a more simplistic model of the virus is adopted, in which, differently from (Kurtin et al., 2020), the interactions are only possible among static neighbouring nodes. The transition among states for the individuals are not obtained using derivatives, but they are ruled by probabilistic conditions. In this way, the complexity of both the virus' behaviour and the simulation itself results to be lower and the understanding of the overall procedure might result more intuitive.

3 BEHAVIOUR OF THE VIRUS

There are two main characteristics that make a virus lethal: infectivity and death rate. Let us consider a network represented by an undirected graph. Starting from a random node, the infection spreads across the network. Since the viral quantity of the virus in the human body follows an exponential trend over time as $N_t = N_{+\infty}(1 - e^{-\lambda t})$, it is reasonable to assume that if person i has been infected at time 0, the probability of infecting each neighbour is defined as: $p_i = \alpha_i(1 - e^{-\lambda t})$ while the probability of his death is $q_i = \beta_i(1 - e^{-\lambda t})$, where both α_i and β_i are distributed according to Beta distributions, characterized by different parameters (see Figure 1), and λ is the parameter to be optimized in order to maximize the number of deaths. We can consider the following five states for each node:

- *Healthy*: the person was not infected with the virus;
- *Contagious*: the person was infected with the virus and has a viral quantity different from zero,

therefore she/he can infect other people;

- *Ill*: as soon as the viral quantity exceeds the threshold value h , $1 - e^{-\lambda t} \geq h$, the person becomes ill and she/he is removed from the network, in this way the quarantine period is simulated;
- *Recovered*: the ill person survived for T timestamps, hence she/he is considered healed;
- *Dead*: the ill person could not recover within the T timestamps, therefore she/he is considered dead.

Figure 2 shows the flow diagram of the states a node might go through during the simulation. Considering implementation issues, the most suitable layer for supporting the described, flexible behaviour is represented by an XML data storage layer (e.g., (Cannataro et al., 2002b; Bonifati and Cuzzocrea, 2007; Cannataro et al., 2002a; Cuzzocrea et al., 2009a)).

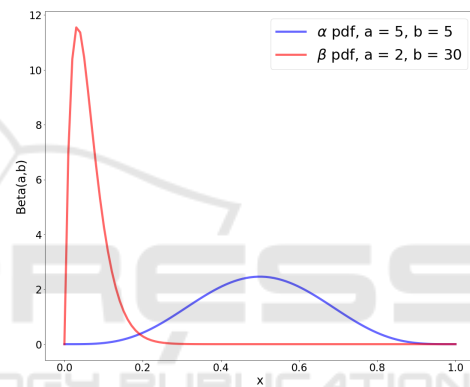


Figure 1: Beta distributions for both probability p to infect someone else and probability q to die and the relative parameters.

4 THE NETWORK GRAPH

The network that has been considered is a 3000 nodes undirected stochastic block model graph composed by three communities. The composition of the communities is defined in such a way that the three communities include, respectively, 14%, 50% and 36% of the total number of nodes. The connections among nodes in the graph are established according to the symmetric edge probability matrix P ,

$$P = \begin{pmatrix} 0.01 & 0.001 & 0.001 \\ 0.001 & 0.005 & 0.0008 \\ 0.001 & 0.0008 & 0.005 \end{pmatrix}$$

The elements on the diagonal of matrix P describe the probability to establish connections between nodes within the same community, while the off-diagonal elements describe the probability to connect nodes belonging to different communities. Being

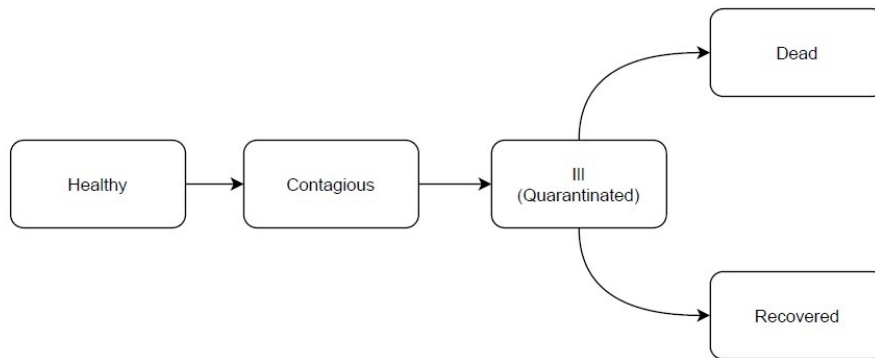


Figure 2: Flow diagram of node's states.

the probabilities in matrix P quite small, it is likely that some nodes will be isolated and, since patient zero is randomly picked at the beginning of the simulation, in order to let the virus spread carry on, each node is forced to have at least degree 3. The obtained network has an average degree of 7.842, an average node closeness centrality equal to 0.241 and its degree distribution is shown in Figure 4. The graph is shown in Figure 3 and it is possible to identify the three distinct communities composing the stochastic block model graph.

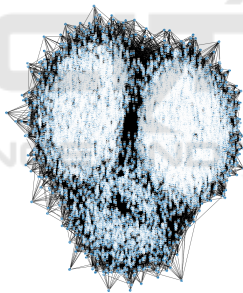


Figure 3: The actual graph of 3000 nodes.

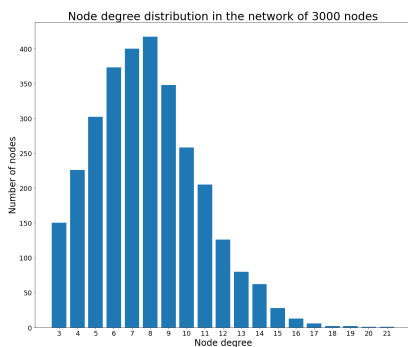


Figure 4: Degree distribution for the stochastic block model graph of 3000 nodes.

Each node has also been characterized by an additional information, the *degree category*, which identifies the connectivity in broad terms of the node itself

towards the other nodes. In order to obtain this information, the values of the node degree distribution are subdivided into five categories. The five possible degree categories are: *very low*, *low*, *medium*, *high* and *very high*. By observing the degree category distribution in Figure 5, it becomes clear that the vast majority of the nodes are characterized by a degree category which is either *very low*, *low* or *medium*; very few are, instead, characterized by a *very high* degree category. This additional information is necessary to observe the behaviour of the virus spread by selecting a different degree category for the patient zero.

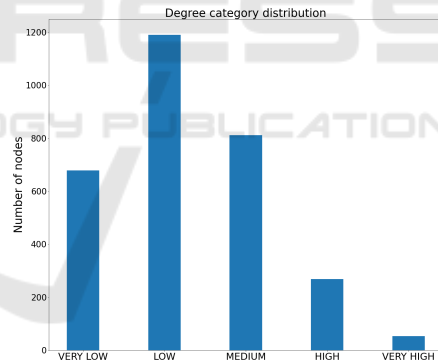


Figure 5: Degree category distribution of the nodes in the graph.

5 THE SIMULATION

Having defined the graph, the parameters of the nodes populating the graph are initialized.

More in detail, for a node i , the probability to infect p_i and the probability to die q_i are set to zero, since at the beginning of the simulation all the nodes are assumed to be healthy, and the parameters α_i and β_i , which rule respectively p_i and q_i , are drawn from the beta distributions.

The experiment is a discrete-event simulation which takes as input the graph with its nodes and the

maximum duration in timestamps. It is also possible to specify as input the degree category of the patient zero or to select a specific node as patient zero. Each timestamp of the simulation corresponds to 2 days.

5.1 Infection and Illness

In the first iteration, the patient zero node is set to be contagious, which means that for the next iterations it is able to infect other nodes. In the following iterations, the contagious node i try to infect its neighbors. To decide whether the neighbor node j is infected or not by the node i , a random number is extracted from a uniform distribution and, if it is less than p_i , also node j becomes contagious. Since the probability p_i and the viral quantity are time dependent, their values are updated at each iteration for all the contagious nodes. Sooner or later, the viral quantity of a contagious node will exceed the threshold h . The occurrence of this event causes a state change for the node, from the *contagious* state to the *ill* state and, from now on, the node is forced to be in quarantine, therefore it is not able to infect other nodes anymore. As soon as the node becomes ill, a local counter is initialized and incremented, iteration by iteration, for the whole illness period, and its probability to die q is initialized. For each iteration during which the node is in the ill state, the value of q is updated, being also its value time dependent.

5.2 Death

Once the node i is ill, at each new iteration a random number is drawn from a uniform distribution. If this random number is smaller than the probability to die, q_i , the node is considered dead, otherwise it survives for another iteration.

5.3 Healing

If the node is strong enough to survive the virus for a number of iterations equal to T , the node is considered *recovered*. At this point the node is immune to the virus, it can not be infected anymore and neither it can infect other nodes.

5.4 End of the Simulation

The simulation stops as soon as all the nodes within the network are either healthy, healed or dead. This scenario corresponds to not having contagious nodes anymore, the virus spread is stopped and, in the remaining iterations, the ill nodes fight for their lives.

6 REAL PARAMETERS DISCOVERY

The goal of the research is to maximize the mortality of the virus. Since the virus behaviour is driven by the parameters h , T and λ , by setting the values of h and T to extremely high numbers, all the nodes of the network will eventually die. This would make the optimization problem trivial.

In order to model a realistic virus, the infectivity and mortality targets are defined. The first one is set to 40%, while the second one to 7%¹. The percentages refer to the total amount of nodes in the network.

Several values for h and T are tested, and the pairs of values that, jointly, get the closest to the percentage targets are considered. The values for λ are taken in the interval (0,1), excluding the extremes, which would give contagious and death probabilities that are either null or quickly converging to α_i and β_i .

More in detail, the analyzed values for h , T and λ are taken from the following ranges:

- $h \in [0.3, 0.6]$, with a step of 0.05;
- $T \in [3, 4, 5, 6]$;
- $\lambda \in [0.05, 0.99]$, with a step of 0.05.

The discovery of the real (h, T) parameters has been carried out by selecting a patient zero node with a degree category equal to *medium*. This choice provides results that are far away from the extreme scenarios about having either a very scarce neighborhood or a very populated one.

For each executed simulation, characterized by a specific triplet (h, T, λ) , the discrepancy between the actual percentage of infected nodes and the infectivity target is computed. Similarly, the discrepancy between the actual number of deaths and death target is also discovered. The two discrepancies are then summed up. Therefore, for each duplet of tested values (h, T) , an overall distance from the targets is obtained.

Sorting the pairs (h, T) by ascending order with respect to the distance from the targets, only those ones with a distance smaller than 500 are kept. The real values for (h, T) are discovered by averaging the obtained values. The whole list of obtained results is shown in the following table:

The reason behind considering all the pairs (h, T) with a distance from the targets lower than 500 relies on the fact that, being the simulation a random experiment, the same triplet (h, T, λ) could provide slightly

¹Percentages were chosen considering past pandemics, such as the infections around the world caused by the Spanish influenza and the deaths for syphilis in Europe during the XV century (Morens et al., 2020).

Table 1: The (h, T) pairs closest to the chosen target.

h	T	<i>sum of target differences</i>
0.3	3	17
0.45	3	136
0.4	3	176
0.35	3	229
0.55	5	342
0.45	5	372
0.3	6	374
0.3	3	432
0.5	3	434
0.3	5	446
0.55	3	487

different results over different experiments. Hence, to alleviate this variability, a larger set of results was considered.

The obtained real (h, T) parameters, for the network of 3000 nodes, are the following:

- $h = 0.45$;
- $T = 4$.

7 LAMBDA OPTIMIZATION

In classical literature, optimization is a critical aspect to be considered (e.g., (Cuzzocrea, 2005; Cuzzocrea and Chakravarthy, 2010; Cuzzocrea et al., 2009b; Cuzzocrea et al., 2003; Ceci et al., 2015)). With similar emphasis, here we focus on how to improve simulation runs.

Now that the real (h, T) parameters have been discovered, the focus is aimed at λ and its value that achieves the highest number of deaths in the network.

The analyzed values of λ are taken from the following range:

- $\lambda \in [0.2, 0.7]$, with a step of 0.01.

So now, a more detailed range for λ is considered. The reason why the range extremes have been reduced is given by the fact that some values of λ , either too high or too small, provide results too far from the virus targets previously discussed (6).

Running different simulations, the just discovered real parameters (h, T) are kept fixed, while λ is let vary in the mentioned range.

The patient zero, for each simulation, has been drawn from the list of nodes of the *medium* degree category, and the number of executed simulations is such that 20% of the nodes belonging to it are selected. The reason behind this broad research is to provide a more reliable assessment on the optimal λ value, considering the stochastic nature of the simulation.

The λ values that achieved the highest number of deaths are reported in Figure 6.

The selected value for the optimal lambda corresponds to the most recurrent lambda that achieved the highest number of deaths. Therefore, $\lambda_{opt} = 0.59$ is the selected optimal lambda.

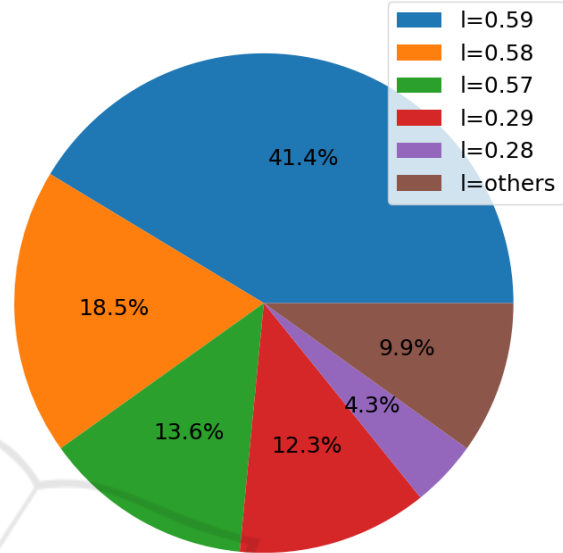


Figure 6: The five most recurrent lambdas that achieved the highest number of deaths.

8 FINAL SIMULATION WITH THE DISCOVERED PARAMETERS

The triplet of parameters (h, T, λ) , that jointly satisfies the infectivity and death targets and provides the most deaths, has been discovered. A final single simulation has been executed to analyze the virus spread evolution over time and the nodes behaviour. Figure 7 shows the results of the simulation. The patient zero is randomly selected from the subset of nodes with a *medium* degree category.

The simulation lasts 21 iterations, therefore the virus spread takes 42 days to cease. One third of the nodes never gets in touch with contagious nodes, and most of the infected nodes heal from the virus, as expected. Also the total amount of ill and dead nodes roughly respects the imposed targets; unfortunately, it not possible to totally respect the targets, because of the random nature of the simulation.

It can be also noticed that the temporal evolution of the virus spread follows the SIR epidemic trend (Keeling and Danon, 2009), in which, starting with all the nodes being healthy, the infection begins and

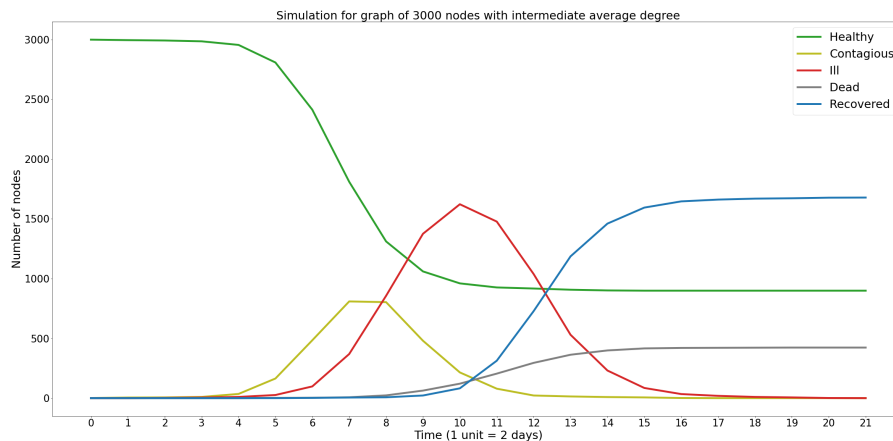


Figure 7: Network behaviour, patient zero of degree “MEDIUM”.

the number of ill nodes starts increasing. Once the peak of ill nodes reaches its maximum, both recovered and dead nodes increase, until a stable situation is reached.

In order to further exploit and extend the described simulation model, network-based solutions would be necessary (e.g., (Cuzzocrea et al., 2005; Cuzzocrea et al., 2004; Bellatreche et al., 2010)).

9 CONCLUSIONS AND FUTURE WORK

The analysis carried out in this report shows that it is possible to model a realistic virus’ behaviour, that satisfies both illness and death targets, by properly tuning the modelling parameters.

Furthermore, it has been shown that the network characteristics play a fundamental role on the outcome of the experiment. It is fair to state that, as the overall connectivity of network increases, the virus spreads more efficiently in the network, which might be intuitive.

It has been also proved that the degree of the patient zero has a great impact on the development of the virus spread, which confirms that a prompt containment of the virus is extremely effective to reduce the virus spread, especially if the virus outbreak starts in less connected portions of the network.

Obviously, the characteristics of the virus play a major role. It has been discovered that the best setting allows the virus to quickly spread and have a high probability to kill the ill nodes, but not high enough to cause the immediate death of the contagious nodes, which would result in the death of the virus itself. This means that, in a real case scenario, it would not be sufficient for the health system to monitor only dis-

eases causing severe symptoms.

Finally, it may be said that the employed virus model is quite simplistic, described by few parameters, but it shows a glance of a general behaviour for the spread of a virus, similar to the more sophisticated SIR model.

Future work is mainly oriented to apply the described simulation framework to innovative big data applications (e.g., (Braun et al., 2017; Audu et al., 2019; Ahn et al., 2019; Morris et al., 2018)).

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