Dynamic Contact Network Analysis in Hospital Wards

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Abstract. We analyse a huge and very precise trace of contact data collected during 6 months on the entire population of a rehabilitation hospital. We investigate the graph structure of the average daily contact network. Our main results are to unveil striking properties of this structure in the considered hospital, and to present a methodology that can be used for analysing any dynamic complex network where nodes are classified into groups.

The MOSAR project aims at examining the factors determining the dynamics of AMRB (AntiMicrobial Resistant Bacteria) spread within healthcare facilities. To further reduce transmission, in addition to classical prevention measures (such as admission controls, isolation of carriers and hand hygiene), changing contacts within the hospital is considered as the next step [1]. Indeed, contacts strongly influence how transmission occurs [2]. Yet, contacts are difficult to measure efficiently in practice, and they may even be harder to change. Recently, however, advances in communication technologies have made it possible to record person-to-person interactions with unprecedented detail, allowing an in depth view of the structure of contacts in real-life settings [3]. If such contacts actually support transmission, it may open the way to further improvement in hospital hygiene.

In this article, we analyse the contact trace recorded on the entire population of a rehabilitation hospital during 6 months between June and November 2009, within the MOSAR project. We focus on a period of 8 weeks of the measurement, from July 6th to September 2nd involving 492 individuals, 253 patients and 239 staffs. We describe the methodology we used to uncover the key characteristics of this dynamic contact network and the main results we obtained: we point out big differences in the contact profiles of services (Sec. 1), as well as in contact patterns of patients and staffs (Sec. 2), and we reveal the structure of interconnections between the mainly introverted services of the hospital (Sec. 3).

Related works There have been some works using sensor devices in order to unfold contact patterns among individuals in environments involving patients or children, which present critical risks for spreading of diseases. The measurement analysed in [4] was made on an entire primary school during 3 days. Two similar experiments, described in [5,6], were both conducted during one week in some paediatric ward. Compared to those works, our analyses present two important advantages. Firstly, the measurement we use was made on a much longer period of time (6 months), which allows to assess the generality of the conclusions we can derive on shorter period of times (like one day or one week). Secondly, our measurement is not limited to a specific part of the hospital, it involves all patients and all staffs of all services of the hospital, which is a key point to have an accurate view of the actual possibility of spreading into a given service. Indeed, these possibilities highly depend on the contacts occurring outside the service under study.

Preliminaries The contact data was recorded using sensor devices carried by the participants and that send signals every 30s. Those signals include the ID of their source device which is recorded together with a time stamp by devices that are close enough from this source (typically 1 to 2 meters). The sending time of the different sensors are not synchronised but their internal clocks are. Afterwards, time is sliced in slots of 30s and we keep, for each slot, the list of pairs A, B of sensors such that at least one (possibly both) recorded the signal of the other. Each of these pairs is unordered (we do not keep track of which node receives the signal and which one sends it) and appears at most once in a given time slot. Finally, in all this article, we manipulate intervals of contacts instead of punctual contacts, i.e. a *contact* is a quadruplet (A, B, t_s, t_e) where A and B are two nodes of the network and t_s and t_e are respectively the time slots where starts and ends the interval of contact between A and B, the *length* of the contact being $t_e - t_s$.

Throughout the article, we analyse sets of contacts over a specified time period (typically one day) using three parameters: number of contacts, cumulated length of contacts and number of adjacency pairs. (A, B) is an adjacency pair on a given time period iff there is at least one contact between A and B during this period. A contact (A, B, t_s, t_e) between A and B gives rise to two *semi-contacts*: one attached to A, denoted $(A, t_s, t_e)^B$, and one attached to B, denoted $(B, t_s, t_e)^B$. And similarly, every adjacency pair gives rise to two *adjacency semi-pairs*. In the rest of the article, for sake of simplicity of vocabulary, we use the term contact (resp. pair) instead of semi-contact (resp. semi-pair), but all statistics are actually made using semi-contacts (resp. semi-pairs). The reason is that it gives a straightforward meaning to mean statistics per individual.

In the rest of the article, for sake of comparison, we make extensive use of a uniformised version of the network of the hospital, which we call the *full-uniform network* and which is defined as follows. The full-uniform network is a complete weighted graph where each pair of nodes receives 1) a weight equal to the density of the real network (i.e.the mean number of adjacency pairs per pair of nodes in the real network), 2) a number of contacts equal to the mean number of contacts per pair of nodes, and 3) a cumulated length of contacts equal to the mean cumulated length per pair of nodes.

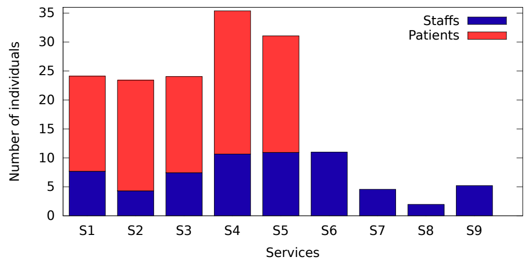

Fig. 1: Number of individuals per day for each service, distinguishing between patients (light red) and staffs (deep blue).

General organisation of the hospital Over the period of study, the mean number of people present in the hospital in one day is about 103 patients and 64 staffs. The patients and staffs are divided into 9 services (see repartition on Fig. 1), only the first five of which (S1 to S5) contain both patients and staffs, the other four (S6 to S9) containing only staffs. Each of the services S1 to S5, containing both patients and staffs, occupies one floor in one of the two wings of the building: S1, S2 and S3 occupy respectively the 1st, 2nd and 3rd floor of the 1st wing, while services S4 and S5 occupy the 2nd and 3rd floor of the 2nd wing. Services S7 to S9 contain rehabilitation staffs and S6 is the night service, regrouping people replacing staffs from services S1 to S5 during nights. S7 and S8 are located in two distinct places between the two wings of the buildings, but S6 and S9 do not have a unique location in the hospital. It must be clear that the division of the hospital into services is not meaningful only from an administrative point of view but has also a strong impact on the structure of the network: in average in one day, 66% of the adjacency pairs of the hospital occur inside services, and 92% of the cumulated length of contacts, while these values are only 25% in the full-uniform network.

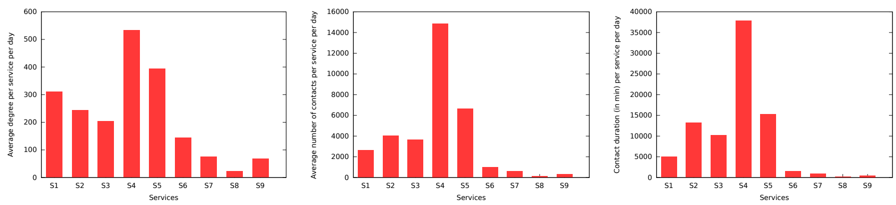

Fig. 2: Mean activity per day in each service. Left: number of adjacency pairs. Centre: number of contacts. Right: cumulated length of contacts.

1 Different levels of activity of services

Figure 2 shows the repartition of contacts among the 9 services of the hospital, in terms of total number of adjacency pairs (left), number of contacts (centre) and cumulated length of contacts (right). It reveals some big differences between services. The 5 services including patients seem to be more active than the 4 others, for each of the three criteria. But there are also clear differences between these 5 services as well. As one may guess, one reason for this is that services have different sizes (see Fig. 1). For adjacency pairs, this is confirmed by the fact that the number of mean adjacency pairs per individual per day varies only little between two different services (Fig. 3 left). On the other hand, the number of contacts and the cumulated length of contacts per day remain very different from one service to another even when computed in average for one individual (Fig. 3 centre and right). This indicates that for these two criteria, the sizes of services cannot be hold for entirely responsible of the disparities between global activity of services appearing on Fig. 2.

Services S6 to S9, which do not include any patients, have a mean number of contacts and cumulated length of contacts per individual which is far less than those of services S1 to S5, which do include patients (Fig. 3 centre and right). Moreover, among these latter services, it appears that services S4, S5 and S2 present a higher mean individual activity, for these two parameters, than services S1 and S3; and it turns out that S4, S5 and S2 are the 3 services that contain the greater number of patients (see Fig. 1). These observations suggest that the individual activity of patients wrt. number of contacts and cumulated length of contacts may be much higher than the one of staffs.

Another interesting fact revealed by Fig. 2 and 3 is that the number of contacts and the cumulated length of contacts per service behave very similarly. We conducted more analyses (not presented here) which showed that this is a more general fact, not only visible for services: for one node over the whole period of study, these two parameters appear to be strongly correlated. Therefore, as they give very similar results in all the experiments we conducted, we chose to keep only one of them in the rest of the paper, namely the cumulated length of contacts.

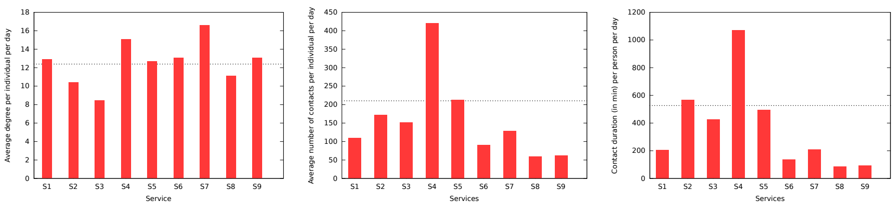

Fig. 3: Mean individual activity per day in each service. Left: number of adjacency pairs. Centre: number of contacts. Right: cumulated length of contacts. The doted lines depicts the mean values per individual in the hospital.

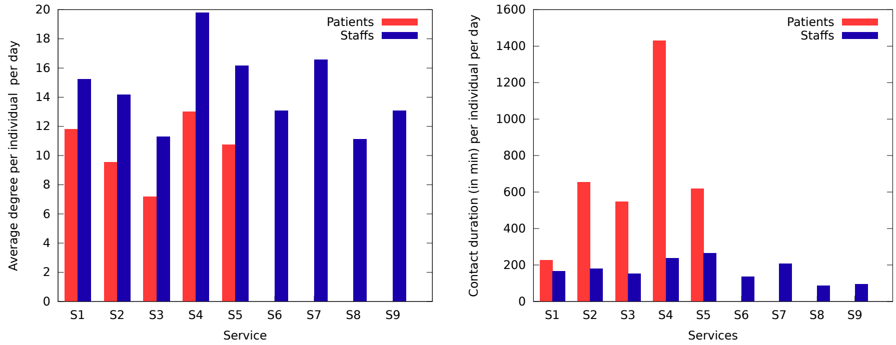

Fig. 4: Mean individual activity per day in each service, distinguishing between patients (light red) and staffs (deep blue). Left: number of adjacency pairs. Right: cumulated length of contacts.

2 Different behaviours of patients and staffs

As pointed out above, patients and staffs seem to have a very different activity. We then refine our analysis of the mean activity per individual and per day by separating patients from staffs in the 5 concerned services (Fig. 4). It turns out that patients are a bit less active than staffs (about 20% to 30% less) in terms of adjacency pairs, but are much more active in terms of cumulated length of contact (between 2 and 6 times more, except for service S1 where cumulated length of contacts of patients and staffs are comparable). This explains why the differences between services that appeared on Fig. 2 left for the whole service disappear when considering the adjacency pairs per person (Fig. 3 left), while this difference does not disappear for cumulated length (see Fig. 2 right and Fig. 3 right).

This rises an even more accurate question: what is the role of patients and staffs in the global contact pattern of the hospital? Where is located the majority of contacts? between patients, between staffs or between patients and staffs? Table 1 shows that a vast majority of the cumulated length of contacts in the hospital (80%) occurs between two patients, while only 12% of this length involve one patient and one staff, and 8% involve two staffs. Nevertheless, the picture for adjacency pairs is quite different: those between patients represent only 24% of all pairs, which is about 35% less than in the full-uniform network. The majority of adjacency pairs (56%) involves one patient and one staff, and 20% of them involve two staffs. Both of these values are about 20% higher than in the full-uniform network, suggesting that the contacts of staffs and in particular the contacts between staffs and patients are very important for the structure of the network, and may then play a key role regarding the possibility of spreading in the hospital.

	PA-PA	PA-ST	ST-ST
Pairs	0.24	0.56	0.20
Length	0.80	0.12	0.08

(a) Global repartition

PA vs	PA	ST
Pairs	0.46	0.54
Length	0.93	0.07

(b) Patients centred

ST vs	PA	ST
Pairs	0.60	0.40
Length	0.42	0.58

(c) Staffs centred

Table 1: Repartition of contacts between patients and staffs in the hospital.

Table 1 centre and right give the repartition of contacts respectively for an average patient and an average staff. They show that the majority of the adjacency pairs of a patient (54%) occurs with a staff, and that the majority of the adjacency pairs of a staff (60%) occurs with a patient. Note that, opposite to the the case of patients whose cumulated length of contacts is strongly unbalanced in favour of contacts with patients (93%), staffs share much more equitably their length of contacts between patients (42%) and staffs (58%). This confirms that staffs present a more open pattern of contacts than the one of patients, which may result for them in particular spreading abilities.

3 Introversion and interconnection of services

In the introduction, we mentioned that most of the activity of the network takes place inside services. Here we investigate further this question by examining the *deviation* of introversion of each service with regard to adjacency pairs, number of contacts and cumulated length of contacts. The introversion of a service S with regard to one of these 3 parameters, denoted α, is defined as $\alpha_{int}(S)/\alpha_{ext}(S)$, where $\alpha_{int}(S)$ is the value of parameter α (e.g. number of adjacency pairs) inside S and $\alpha_{ext}(S)$ is the value of parameter α between S and the rest of the hospital. In all the rest of the article, we qualify contacts and adjacency pairs as *internal* or *external* depending whether they take place inside a service or between two distinct services. We define the *factor of deviation* of introversion of service S as the ratio between the introversion of S in the real network and the introversion of S in some specifically defined uniform network. For adjacency pairs, we use for comparison the full-uniform network defined in the preliminaries. For number of contacts, we use the *contact-uniform network*, which has exactly the same adjacency pairs as the real network, each of which receives a number of contacts equal to the mean number of contacts per adjacency pair in the real network. And finally, for cumulated length of contacts we use the *length-uniform network*, which has the same adjacency pairs as the real network, each of which has the same number of contacts as in the real network, but each of this contacts receives a length equal to the mean cumulated length per contact in the real network. The rational behind these definitions is that for the number of contacts, we compute its deviation knowing the adjacency pairs of the real network, and for the cumulated length of contacts, we compute its deviation knowing both the adjacency pairs and the number of contacts of the real network.

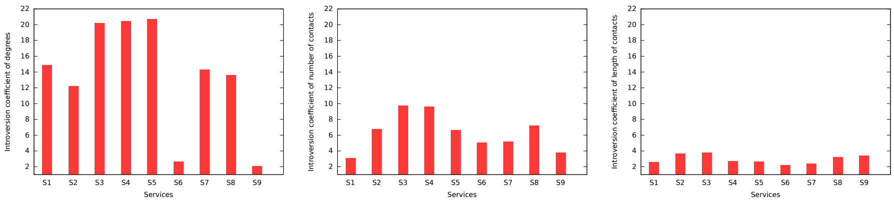

Fig. 5: Factor of deviation of the introversion per day for each service. Left: deviation of the introversion wrt. number of adjacency pairs. Centre: deviation of the introversion wrt. number of contacts, knowing adjacency pairs. Right: deviation of the introversion wrt. cumulated length of contacts, knowing adjacency pairs and number of contacts.

The results are depicted on Fig. 5. They show that services are strongly introverted in terms of adjacency pairs: most of them have a factor of deviation of introversion between 9 and 18, except two services S6 and S9 having factors 2 and 3. Note that these two services are those that do not have a single location in the building of the hospital. Going further, even knowing this structure of the adjacency pairs, services are still clearly introverted in terms of number of contacts (factors between 3 and 10). This means that services do not have only a strong preference for making adjacency pairs inside rather than outside, but they are also much more likely to repeat contacts for their internal adjacency pairs. For cumulated length, the factor of deviation of introversion is between 2 and 4 for all services. The fact that these values are lower than the previous ones is a consequence of the correlation between cumulated length of contacts and number of contacts (see Section 1). But still, they indicate that services not only favour internal adjacency pairs and internal repetition of contacts, but also prefer longer contacts between their members rather than outside.

	PA-PA	PA-ST	ST-ST	Total
External	0.05	0.23	0.06	0.34
Internal	0.19	0.33	0.14	0.66
Total	0.24	0.56	0.20	1.00

(a) Global repartition.

PA vs	PA	ST	Total
Ext.	0.10	0.22	0.32
Int.	0.36	0.32	0.68
Total	0.46	0.54	1

(b) Patients centred.

ST vs	PA	ST	Total
Ext.	0.24	0.12	0.36
Int.	0.34	0.30	0.64
Total	0.58	0.42	1

(c) Staffs centred.

Table 2: Repartition of adjacency pairs between patients and staffs, distinguishing between internal and external pairs.

Table 2 gives some global statistics distinguishing both between internal and external contacts and between patients and staffs. It reveals a strong bipartite-like structure of the network between the staffs divided into services on one side (9 classes), and the patients divided into services on the other side (5 classes).

Indeed, more than 83% of the links between these 14 classes occur between one patient and one staff. In addition, links between patients and staffs represent more than 67% of the external links between services of the hospital (18% of these links occur between staffs and 15% between patients). This shows that the contacts between patients and staffs play a prevalent role in connecting the introverted services of the hospital. These observations are confirmed from an individual centred point of view (see Tab. 2 centre and right): an individual (either patient or staff) has only few external adjacency pairs with his own side of the bipartition, while the repartition between its external and internal pairs with the other side are more balanced than internal/external pairs in the whole network.

Perspectives

The main perspective of our work is to determine the impact of the specific structure of contacts we highlighted on spreading processes. In this context, it is still to establish whether there is a correlation between the contaminations contained in the MOSAR dataset (which also includes biological data) and the pattern of contacts in the dynamic network. The second perspective is to take into account the variation of the contact pattern of the hospital along time and determine its impact on the possibility of spreading in the network.

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