

New Algorithm for Distributed Frequency Assignments in IEEE 802.11

Wireless Networks

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Abstract: The continuous growth of IEEE 802.11 wireless local area networks (WLAN) brings the benefit of a high speed wireless access to packet networks, such as Internet. But it also entails the successive appearance of new unresolved problems. One of these problems consists in the degradation of the performance observed by the users when there is a great number of radio networks coexisting in the same area. In densely populated zones it is not strange to find WLANs of different nature (private, public, etc.) sharing a scarce resource as it is the radio spectrum. This problem can be mitigated with an appropriate channel allocation. In this paper we present an algorithm for the frequency assignment problem (FAP) in IEEE 802.11, based on classical graph colouring but adding the objective of reducing interferences among overlapping cells, and thus improving the global throughput performance. An accurate evaluation of interferences is obtained not only measuring power levels, but also being aware of traffic load. Important performance improvements have been observed on a real scenario.

1. Introduction

At the present time, a great proliferation of wireless access packet networks is clearly taking place due to a growing demand of bandwidth and mobility from users. The technology evolves to face this increasing demand, and a good example is the arrival of 3rd generation of mobile radio systems. The expectations generated by their arrival are not being fulfilled at the moment, and competitor technologies are taking benefit from that fact, especially the wireless networks based on the IEEE 802.11 standards. This technology presents important disadvantages if compared with other radio networks, as a shorter range, security issues, difficulties providing inter-network or inter-operator roaming, etc. However, the networks based on the IEEE 802.11 are unquestionably being chosen by most of the users. Its popularity comes noticeable, beyond the evident advantages of the radio networks as opposed to the wired networks, by a low cost hardware, great interoperability thanks to the Wi-Fi partnership influence and because they provide a bandwidth that is several orders of magnitude above the available right now by means of 2,5G or 3G.

Nowadays it is a common thing to see the coexistence of many WLAN networks in densely populated areas, either of private or of public nature

(Hot-Spots), corporative, etc. Domestic users use it to avoid the installation of new wires in their homes and to communicate with other users, in offices or university campuses are used to provide access to Internet or corporative Intranets to their employees or students and, lately, operators and ISPs have found a new market offering this access in public places, like hotels, airports or convention centers. With a high density of nodes, the presence of interference increases causing the performance perceived by users to degrade. In order to reduce the effect of interferences in cellular networks, a frequency planning is traditionally used. In the case of 802.11b and 802.11g WLAN networks, frequency channels are a scarce resource since we can only count on 3 noninterfering channels. The frequency assignment problem (FAP) is therefore, an important issue to solve.

IEEE 802.11 devices use the 2.4GHz ISM (Industrial Scientific Medical) unlicensed band. These bands can be used freely though respecting the legal limits for transmission power (below 100mW EIRP). Therefore there is a slight control over it, so when the selection of the more suitable channels takes place, we must consider that there may be other devices using part of the same ISM band. Although different spread spectrum techniques are defined (DSSS or FHSS) in order to minimize the effect of interferences, the coexistence of different types of devices in nearby channels can seriously degrade the performance of a WLAN.

In the case of IEEE 802.11b/g and according to European regulatory bodies, 13 channels are defined, whose carriers go from 2.412 (channel 1), to 2.472GHz (channel 13), with a spacing of 5MHz. The spread signal bandwidth is about 24MHz, allowing as much as three nonoverlapping channels (e.g. 1, 6 and 11). Anyway, there are studies stating that a good performance is guaranteed using a separation of four channels [1] between carriers, so the range of possible channels is extended to four (1, 5, 9 and 13); other studies go further on and assure that up to five channels can be used: 1, 4, 7, 10 and 13 [2], but the later results are not generalizable since their calculations are based on specific hardware; [3] comes to the conclusion that the minimum separation between channels not to observe performance degradation, also depends on the hardware used, but in general, a minimum gap of 5 (e.g. 1, 6 and 11) is desirable.

The way the nodes of a WLAN share the medium is similar to an Ethernet segment. A CSMA/CA (carrier

sense and collision avoidance) is used as medium access control scheme. This makes the study of interferences in WLAN 802.11 quite different from what is done in other radio networks due to the particular influence of interferences produced by cells using the same channel (co-channel interference). Although not deeply studied, in [4] it is shown that sometimes it is better to have adjacent channel interference rather than co-channel. For that reason we think that frequency assignments in WLAN 802.11 should allow the use of all possible channels and not only the nonoverlapping three.

In this paper we analyze the channel allocation problem in WLAN 802.11b/g networks and as a solution we contemplate the use of the 13 possible channels in order to get assignments with less interference. Furthermore, it can be applied in a distributed way, allowing the calculation of an assignment in different nodes of one or several networks. Next section is an overview of the channel allocation problem in 802.11 networks. Section 3 describes the proposed algorithm, whose main snag, the co-channel interference, is studied in section 4. Finally, after having shown some practical results on section 5, we give the conclusions and future work.

2. Frequency Assignment Problem in 802.11

In most of the literature, frequency assignments in WLAN 802.11 networks are studied as a part on the design of multicellular WLANs working in infrastructure mode. A good design can be evaluated according to two basic requirements: full coverage of the required area and the provision of a capacity suitable to support the traffic that is generated, without degrading the service as the number of users increases. Although there is an endless list of parameters to consider, the requirements mentioned above can be obtained with an exhaustive selection of Access Points (APs) locations and the proper set of channels and power levels.

Many studies have been published contributing to the resolution of this problem with the development of numerous algorithms [5]; either for the planning of general wireless networks [6], or specific for 802.11 networks [7][8][9]. Most of the previous work was based upon the perfect knowledge of the scenario: traffic demand on the different areas to cover, orography and obstacles, etc. Then, an offline calculation is made which evaluates certain parameters to set the configuration of the APs before they are installed. These calculations are intended to obtain the AP location and a frequency assignment that guarantees the best possible coverage, or the best traffic distribution among all the APs. In [8] and [10], ILP (Integer Linear Programming) formulation is used to optimize the maximum channel use and in [11] a heuristic method is studied with the same purpose.

In a more general scenario, more than one WLAN domain shares the frequency resources and the number of APs, client nodes and the traffic demand varies randomly, and thus, the initial settings should be

adapted dynamically to be fit for the new environment. Therefore, a new mechanism is needed for the frequency assignment problem which has the capacity to evolve according to new conditions and which also supports the existence of many different WLANs in the same area. These premises make centralized management solutions difficult to implement, as stated in [4], so we present a method that allows efficient channel assignments to be calculated by any AP itself.

The algorithms for the frequency assignment problem (FAP) can be classified according to their objective. When the purpose is to find a feasible solution that fits certain restrictions, we talk about F-FAP (Feasible Frequency Assignment Problem) or Max-FAP variants (Maximum Service FAP). This is the most widely used method in 802.11 networks; assignments are found which comply with the restriction of 5 channel separation for adjacent cells [8][10][12]. Optimizing the number of channels (MO-FAP: Minimum Order FAP) or the area of the frequency spectrum used (MS-FAP: Minimum Span FAP) does not have sense since the whole ISM band is freely available. As we understand, the best formulation applicable for WLAN 802.11 DCF (Distributed Coordination Function) is the one that aims to minimize interferences among cells, so that the performance of each cell is improved. The FAP formulation whose objective is to minimize interferences is known as MI-FAP (Minimum Interference FAP) and is usually modeled by interference graphs $G = (V, E)$. There are different ways to solve these graphs [13], many of them are designed to find optimal solutions, but they always involve a high computational effort.

3. Proposed algorithm

If two of our objectives were a fast adaptation to changes and an assignment that should be computed on the APs, the algorithm we are looking for must work in a timely manner at a low computational cost. The algorithm we propose is inspired by DSATUR [14] applying the idea proposed in [15] and [16] of adding a certain cost. Thus, this is an algorithm to color the vertices of a graph based on a degree of saturation that is calculated from a certain cost. The algorithm does not always provide the optimal solution but it is fast and requires little resources.

The interference graph G is composed by a set of vertices V , representing the APs in a region, interconnected by a set of edges E . The existence of an edge between two nodes denotes that both APs are within reach of each other (see figure 1).

The DSATUR algorithm establishes the order in which nodes must be colored and the colors (i.e. noninterfering frequencies) to assign. At each iteration, the node with a higher saturation degree (i.e. the node with a larger number of colored neighbours) is selected to be colored. If more than one node has the same saturation degree, the one with the highest ordinary degree (i.e. the node with larger number of neighbours) is selected, if the draw persists, then a random selection is performed. Since the assignment may be computed on different devices and all of them must obtain the

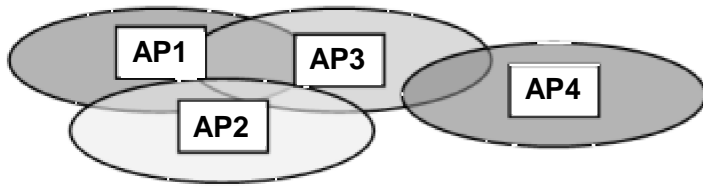


Figure 1a: Coverages of 4 APs

same result, all nondeterministic steps must be replaced; e.g. in [12] ties are broken using the physical address of the nodes. The color assigned to the selected node is the lowest channel not being used on any of its neighbours.

When there is a great density of nodes and edges (e.g. imagine a subset of four vertices, where each vertex is connected with the other three, i.e. a *clique* of 4, see figure 6) and we have just 3 colors (i.e. 3 nonoverlapping channels), this algorithm is not useful since it tries to solve a problem when there is no feasible solution. If we use all existing channels (11 in the U.S.A., 13 in Europe and 14 in Japan), we will obtain feasible solutions for almost every actual scenario, but as stated before, if we use overlapping channels in interfering cells, we will suffer a degradation of the performance. For that reason we introduced some modifications on the algorithm with the aim of minimizing interferences.

The concept of saturation degree is modified with the addition of a certain cost, and the frequency that minimizes this cost is assigned. In our case, the new saturation degree evaluates the interference of a node seen from its neighbours. The idea is as follows:

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while !(f(v) != 0 " v ∈ V) do
  select v with f(v)=0 and maximum saturation
  degree
  f(v) = channel which minimizes interference
  update saturation degree of nodes in V

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where $f(v)$ = channel assigned to node v . For the computation of an interference-based cost, a matrix C whose elements $c[i][j]$ " $i, j \in V$, represent an average of the signal level received in node j from the cell of node i ; $c[i][j] = 0$ means that in graph $G = (V, E)$, the edge $(i, j) \notin E$; $c[i][i] = 0$ " $i \in V$. The sum of the elements of row i of C gives the total interference caused by node i and is used in our algorithm as the main saturation degree. The interference level received by a node may be used likewise, obtaining similar results. In case of having more than one node with the same degree, the decision is taken according to original DSATUR. Global cost is computed as follows:

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initialize cost = 0
for all i ∈ V and f(i) != 0 do
  for all j ∈ V and f(j) != 0 do
    cost = cost + c[i][j]*chFactor(|f(i)-f(j)|)

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where $chFactor(x)$ is the factor by which the interference received x channels apart from the desired signal is filtered. A special case of study is $chFactor(0)$, i.e. we have co-channel interference.

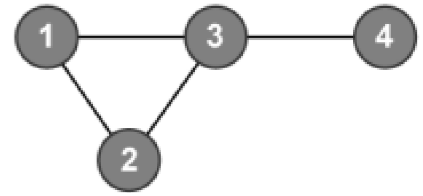


Figure 1b: Interference graph of Fig. 1a

4. Co-Channel/Adjacent channel Interference

As explained before, co-channel interference has an influence over the performance which is slightly different from the interference caused by adjacent channels. For example: there are two overlapping cells using the same channel; if one AP must transmit and when it senses the medium, it detects the other AP or a distant station transmitting, it will defer its transmission even though its own cell is idle; however when the two cells use different frequencies, if an AP wants to transmit, it senses the medium free, but noisy. It will cause errors on reception and the decrease of the effective rate (in bps). Figure 2, obtained after practical measurements, shows the effect of interferences having from 0 to 5 channels of separation between two cells. The scenario consists of two overlapping cells and one client attached to each AP. Both clients are sending, data at maximum rate. While we change the channel of one cell from 1 to 6, we measure the performance of the other cell, which is fixed to channel 1.

Interferences from adjacent channels are treated as noise whose effect over the maximum throughput of a cell can be approximated by means of analytical models like [17] and [18], both based on the Markov chains model of [19], whereas the effect of the co-channel interference has only been studied in very specific testbeds [4].

The effect of interferences from different channels showed in figure 2 does not provide enough information since it consisted of some practical results obtained under particular conditions. It is clear that having a cell working in an adjacent channel and where a high load of traffic is generated, will not have the same influence as another cell without any traffic. It will not be the same if an adjacent cell transmits at a high power level than another cell that is, for example, behind a wall. Actually, evaluating the effect of co-channel compared to adjacent channel interference is a complex issue.

Even though the effect of co-channel interference is more complex, it could be understood as the effect of increasing the number of sources in a cell; in both cases the same medium is shared with a larger number of stations. Figure 3 represents the performance (attended traffic/offered traffic) of two overlapping cells A and B, both of them are using the same channel. In Cell A, the AP keeps generating a fixed amount of traffic equal to the maximum possible throughput available on one cell, whereas the traffic offered in cell B is variable. X-axis represents the traffic offered in cell B in % of the maximum possible throughput.

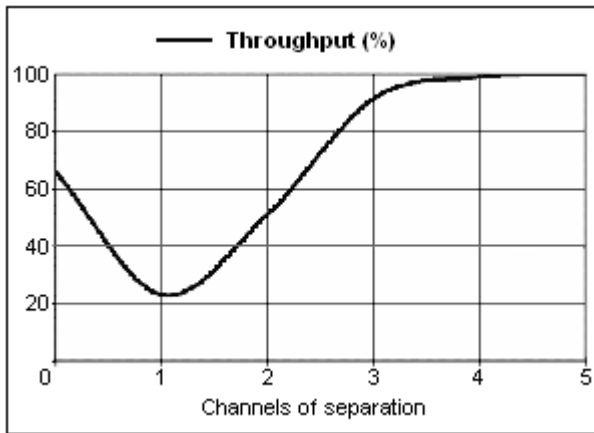


Figure 2: Throughput with interferences

Observing the results, we apply some simplifications knowing the traffic in both cells:

- When the load in a cell represents less than the 60% of the maximum possible throughput in a cell, no matter the amount of co-channel interference, it will not suffer from evident degradation.
- When the sum of the traffics offered in both cells represents less than the 120% of the maximum possible throughput in a cell (and each is less than 100%), none of the cells will suffer from evident degradation.
- When the sum of the traffics offered in both cells is greater than the 120% (and each is between 60 and 100%) of the maximum possible throughput in one cell, their throughput is degraded to the point where they obtain as much as the 60% of that maximum.

Note that a value above 100% is achieved; this is because the tests were made with one node generating traffic on each cell. A better performance can be obtained when there are two or three users in a cell, whereas if the number of users keeps growing, the higher probability of collision causes a degradation of the effective throughput.

Knowing the offered traffic and the signal level in the different neighbouring cells, we can compare the effect of both types of interference and we can apply the same units to measure the cost of an assignment. The next simplifications must be considered:

- The average of interference level received from a cell A is computed on its neighbouring APs as the product $\rho_A \cdot P_A$, where ρ_A is the usage of cell A (% of time the medium is not idle) and P_A is the average power level received from cell A. Notice that this is the interference seen from other APs, whose clients will perceive a different value depending on their antenna gain or their position within the cell.
- The usage of a cell may be a parameter provided by one AP to its neighbours, but this data should be kept as an upper bound, since

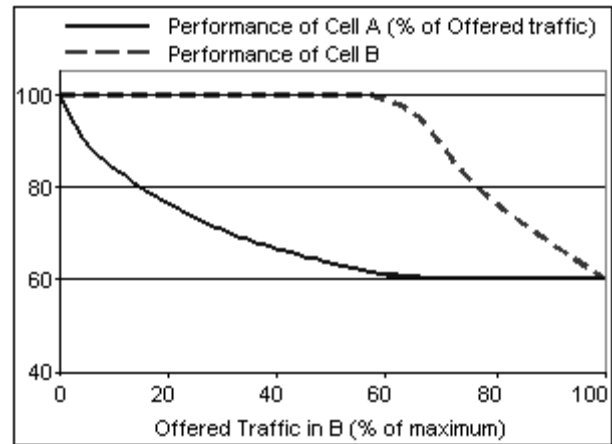


Figure 3: Co-channel interference

the usage actually perceived may be different when sensed from different neighbouring APs. In figure 4, AP2 has 4 active clients associated; AP1 only perceives interferences from one node, whereas AP3 perceives traffic from two nodes.

- The interference in a cell is computed as the sum of the interferences received in the AP and is used to predict the BER (Bit Error Ratio). We know how a concrete BER influences the throughput [17][18], so at last we can compare the effect of co-channel and adjacent channel interference. The BER is in turn approximated using the CIR depending on the modulation used (CCK in [20], QAM, QPSK and BPSK in [21]); we know the interference level; the carrier level can be approximated as the average of the signal received from its clients. Once again, the PER (Packet Error Ratio) will be different if computed in any other node of the cell different from the AP.

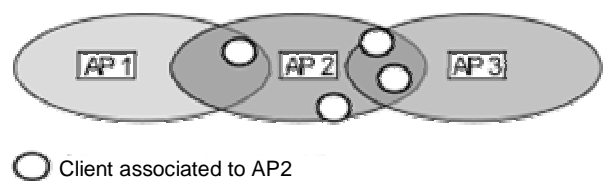


Figure 4: Clients of an AP detected from two different cells

These simplifications would give more realistic information if we were able to gather information from client nodes. That would be possible with the use of additional software in the client device or by adding some modifications in the standard. The former proposal supposes that the system doesn't keep being transparent for the user, the later is hardly viable but possible, since there are known manufacturers implementing mechanisms that extend beacon frames to include more information. Our approximations will also be more accurate if we had a better information supply from the physical layer. In this sense, the proposals of the Radio Resource Measurement Study Group (IEEE 802.11k) are expected to be part of the solution.

5. Experiments and results

A C program was made to generate random graphs which were solved to evaluate the effectiveness of our algorithm. Solving a great number of these graphs we verified that if a feasible solution can be obtained with original DSATUR (i.e. as much as three channels are needed to avoid interferences), will also be obtained with our modification with a cost of 0 (no interferences). When there is no feasible solution with three channels, the assignment provided making use of the 13 possible channels is better than the obtained using only the noninterfering 3. In addition, the assignments provided by the proposed algorithm are compared with the optimal solution (obtained with a sort of branch-and-cut). In the tests we tried to solve randomly generated graphs of 10 to 30 vertices; to our understand, they are representative of most real-life situations. The results showed that our algorithm obtains the optimal solution in more than the 30% of the tests. In the 50% of the tests, the cost we obtain is less than 1.15 times the optimal cost (see figure 5).

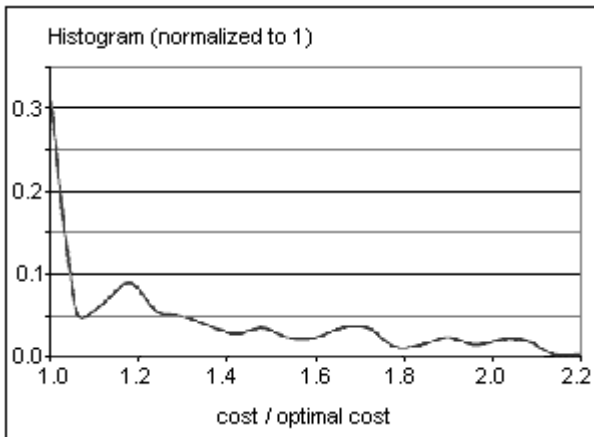


Fig. 5: comparison of obtained cost and optimal cost

We also built a real testbed to verify the previous results and we saw that finding assignments with smaller costs is translated into a better performance. The configuration of the testbed, represented in figure 6 is the simplest topology where interferences cannot be avoided: a *clique* of four nodes. It is not solvable with F-FAP and three colors. The testbed consists of four APs and one client associated to each AP. Coverage areas of the eight nodes are overlapped, i.e. every node “sees” all the others.

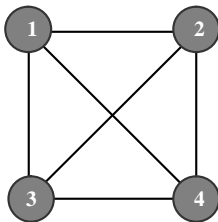


Fig. 6: clique of 4 vertices

The results and configurations of the tested scenarios are summarized in table 1. In the initial situation, one of the APs transmits at a high power level and

generates low traffic, while the rest of the APs radiate low power but are affected by a high load of traffic. If only received power levels are taken into account, the best assignment would be that which minimizes the interference caused by AP1 (1st assignment). Considering not only power levels, but also traffic load, the assignment provided by our algorithm improves the global throughput (2nd assignment). The cost of the first assignment was 8.7, while the cost of the second assignment was 0. This number is related to an equivalent global interference level. Then, the behavior of the nodes is altered in the following way: power of AP1 is reduced and its traffic is increased; the rest of nodes lower their traffic but their transmitted power remains unchanged. The previous assignment may not be the best in the new situation (1st assignment of scenario 2), so a new assignment is computed, by which a better performance is achieved (2nd assignment scenario 2).

6. Future work

When an AP is initialized, it must be able to discover the number of APs within its reach, the signal level received from each of them and their traffic load. With this information the AP is able to select the channel with less interference, only considering the portion of the network it reaches. Assignments obtained that way are locally optimized. In order to obtain a globally optimized assignment using the previously explained algorithm, the knowledge of the whole network is needed for the generation of the cost matrix C . For that reason, the definition of some kind of protocol, similar to the existing link state routing protocols, becomes essential. This idea has already been mentioned in [12].

Moreover, it is clear that we need up to date data, thus, it would be necessary to monitor the medium constantly. This is generally not possible when the AP has clients associated to it, since in monitor mode the AP can only listen, not being able to transmit frames. An added problem resides in the way the nodes exchange information to build the complete graph. If there are networks belonging to different domains, we can't count on a common distribution system (DS). These two problems identified: monitoring and exchange of protocol frames, can have a common solution with the use of two wireless NICs. One of them devoted to serve its clients, and the other one can have two functions: periodically monitor the medium to obtain statistics of neighbouring cells, and create a wireless DS to allow the exchange of the protocol frames. For the creation of that wireless DS, Ad-hoc networking concepts can be applied. In addition, to improve the yield obtained with the use of a second interface, the DS network can be used as backbone for user data as well as our signaling.

7. Conclusions

After having analyzed different mechanisms for the frequency assignment problem in IEEE 802.11 networks, we can say that the use of the traditional three nonoverlapping channels doesn't always provide

Scenario 1			1 st assignment			2 nd assignment		
Node	Mbps	Power	Node	Channel	Throughput	Node	Channel	Throughput
1	0.1	High	1	1	10.18 Mbps	1	1	11.79 Mbps
2	4.0	Middle	2	6		2	1	
3	4.0	Middle	3	11		3	11	
4	4.0	Middle	4	6		4	6	
Scenario 2			1 st assignment			2 nd assignment		
Node	Mbps	Power	Node	Channel	Throughput	Node	Channel	Throughput
1	4.0	Low	1	1	7.66 Mbps	1	1	8.46 Mbps
2	2.5	Middle	2	1		2	6	
3	2.5	Middle	3	11		3	11	
4	2.5	Middle	4	6		4	6	

Table 1: Configuration and results in two different scenarios

the best performance because there are scenarios where the use of the whole ISM band is preferable. As expected, minimizing interferences involves global throughput improvements. For calculation of interferences not only the knowledge of signal levels, but also the traffic load on each cell are needed.

Even though we applied some simplifications, the algorithm presented in this paper is able to find assignments with lower interference cost, and thus, provide better throughput. Our simplifications could be arranged if we could count on more accurate information from physical layer or if we could gather information from the clients associated to an AP. The algorithm is also able to provide fast results with low computational cost. This way it would be possible to run the algorithm in simpler devices (e.g. commercial APs). In exchange, the optimal solution is not guaranteed, but we will be near it.

Furthermore, the use of a fast algorithm allows a quick adaptation to changing environmental conditions, as previously explained, an assignment is no more optimal after a change in the scenario, such as the appearance of a new AP, a change in offered traffic, power levels, etc. But for the calculation of successive assignments, either from a central point or from the APs, we need the knowledge of the whole graph. For that reason the presence of a protocol is required to exchange information among the involved nodes.

Acknowledgments

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