A Down-to-Earth Scheduling Strategy for Dense SINR Wireless Networks

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***Abstract*—This work presents a scheduling strategy for wireless networks under the Signal-to-Interference-plus-Noise Ratio (SINR) model. This model employs the signal-to-noise ratio and the cumulative interference of simultaneous communications as a criterion to determine whether a transmission can be correctly received at the destination. As an advantage, the SINR model allows spatial reuse, i.e. given certain conditions, concurrent communication between multiple devices is possible, even if they are all within the coverage areas of one other. The strategy proposed in this work estimates the interference at the receivers, to determine which sets of devices can transmit simultaneously. The strategy assumes that devices know their positions on the plane and is based on a heuristic according to which transmissions only occur to the closest device. The cumulative interference at receivers is determined based on the analysis of the communications between pairs of devices. The output is a schedule that determines which devices can communicate on consecutive time slots. The strategy was evaluated through simulation, for networks of different densities. Results attest to the effectiveness of the schedules obtained.**

***Index Terms*—Wireless Networks, scheduling, SINR model, spatial reuse**

I. Introduction

There is currently a variety of wireless network standards, each with specific characteristics or tailored for particular types of applications. Those networks usually employ different transmission rates and coverage areas. Different networks generally employ different frequency spectra. Despite the differences, all wireless communications share the same basic technology: data is transmitted using radio frequency waves on a shared medium [1]. Frequently, devices on a given network communicate over the shared channel using the same frequency spectrum. This has the disadvantage of the interference caused by simultaneous transmissions. The interference can impair the quality of received signals, making it impossible for messages to be received correctly. As interference is an phenomenon that is inherent to wireless communications, its effects must be considered when developing any communication strategy for this type of medium [2].

One of the most common ways to deal with interference is to define a schedule for the transmissions, separating transmitting devices in space or time [3]. Scheduling can be defined based on the properties of the communication channel, such as the fact that the power of the transmitted signal fades according to the distance travelled. Depending on the resulting interference, it becomes possible to schedule simultaneous transmissions by devices that are reasonably far apart. The power level of the signal transmitted by a interfering source – which is at a sufficiently large distance from the receiver – can be received at a level small enough so that it does not prevent the correct reception of a signal transmitted by another closer source. The so-called "spatial reuse" allows multiple simultaneous transmissions by devices that use the same frequency spectrum, as long as their interference does not prevent the correct reception by the respective destinations. The greater the number of simultaneous transmissions, the greater the spatial reuse. Spatial reuse has been employed as an evaluation metric for scheduling algorithms [4].

This work adopts the SINR model (*Signal-to-Interference-and-Noise-Ratio*) to represent the wireless communication medium. This model is known to accurately reflect properties inherent to the wireless communication channel [5]. Under this model, several works have been proposed that present communication strategies to allow multiple devices to make simultaneous transmissions, in order to improve the efficiency of the network [6], [7], [8]. In this work we present a time scheduling strategy based on the SINR model. Time is divided in sequential time slots. Each device is scheduled to transmit in a time slot, all devices have to be assigned. If there is no spatial reuse, then n time slots are required for all n devices to communicate, one device per time slot. On the other hand, spatial reuse reduces the total number of slots required for all devices to communicate, and thus also reduces the waiting time it takes for any device to communicate.

Several scheduling strategies for the SINR model have been proposed in the literature, e.g. [4], [6], [9]. Most of the work in the field has been theoretical, with several related computability bounds proved. After checking the state of the art, the actual assumptions and system requirements of the scheduling algorithms available, we selected one of particular interest to implement and evaluate through simulation [10]. That strategy consists of a scheduling algorithm for dense wireless networks that is based on the TDMA access mechanism (*Time Division Multiple Access*) to schedule transmissions.

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The proposal assumes a dense one-hop network: *all* devices are mutually under the same transmission range. The scheduling algorithm organizes devices into a so-called "tournament tree". The tree is built from an algorithm that explores the SINR relationship in simultaneous transmissions to create a graph that connects devices that are located at short geographic distances from each other. On this graph, a coloring algorithm is applied to extract the schedule. Although the correctness of this strategy has been proved in the paper it was presented [10], after implementing that strategy with simulation, we got truly disappointing results: in all the networks simulated the schedules presented no spatial reuse at all [7].

The motivation to develop the strategy proposed in this work was to have a simple scheduling strategy for SINR wireless networks that could be shown to be effective through simulation. The strategy assumes a one-hop network in which all nodes are within the transmission ranges of each other. It assumes that each node knows its position on the plane. Furthermore, in order to improve the chance that multiple simultaneous transmissions can be scheduled for single time slots, the strategy employs a simple heuristics: each device only communicates its closest device. By computing the mutual interferences among the different pairs of communicating devices, it becomes possible to determine which devices can communicate simultaneously. The strategy was implemented with simulation and results show its effectiveness on networks of different densities.

The rest of this work is organized as follows. Section II presents an overview of the SINR model and spatial reuse. In Section III the proposed scheduling strategy is described. Simulation results are presented in Section IV. Finally, the conclusions are in Section V.

II. An Overview of the SINR Model

The SINR (*Signal-to-Interference-plus-Noise Ratio*) model, also known as the physical interference model or physical model, is a model for wireless networks that considers the effects of cumulative interference on signal reception. The model also considers that the power of a transmitted signal fades according to the distance it travels. Several works show the advantages of the model to represent real wireless networks [11], [12].

The SINR model establishes a criterion for a transmission to be correctly received and decoded by the destination. This criterion is based on three properties observed in wireless communication: signal propagation (the fading effect), plus the presence of noise and interference between signals. The model adopted for signal propagation considers that the power of the transmitted signal fades proportionally to the inverse of the distance between the transmitter i and the receiver j, represented by $d(i, j)$, raised to an exponent called *path loss*, α. Noise corresponds to unwanted electrical signals which cannot be controlled and which interfere with the communication signals (signals employed to transmit messages). In the SINR model, the noise is represented by a constant N_0. Interference occurs between simultaneous transmissions. Consider τ simultaneous transmissions. The SINR model computes the interference level at device j as the sum of the $\tau - 1$ simultaneous transmissions, which of course does not include the transmission between i and j.

The criterion for determining whether a transmission is successful is as follows. The ratio between the received signal power and the sum of the powers of all interfering signal plus the noise must be greater than or equal to threshold γ, which is called *SINR threshold* and expressed in decibels (dB), specified as inequality 1.

$$\frac{\frac{P_{Ti}}{d(i,j)^\alpha}}{N_0 + \sum_{\substack{k=1 \\ k\neq i}}^{\tau} \frac{P_{Tk}}{d(kj)^\alpha}} \geq \gamma \tag{1}$$

According to the basic premise of the SINR model it is the cumulative interference power that determines the possibility of the correct reception of a signal [9]. Thus, simultaneous transmissions between devices that share the same frequency spectrum can occur, with the multiple signals being received correctly, as long as the cumulative interference level does not get above the SINR threshold, the point from which correct reception becomes impossible. For simultaneous transmissions to occur, it is necessary to use a scheduling mechanism or algorithm that establishes an order for the transmissions.

A scheduling algorithm can make use of the distances that separate devices to schedule transmissions into time intervals (*slots*). The model allows for the so-called "spatial reuse", with multiple transmissions scheduled to the same *slot*. Consider, as an example, a pair of devices i and j which are closest to each other when compared to the rest of the devices on the network they are on. Also consider that the power radiated by the transmitting device i and received by j is much higher than the cumulative power received from other simultaneous transmissions, which are therefore considered interference. In this example j can receive the signal from i correctly, concurrently with other transmissions. The greater the number of possible transmissions at the same instant of time, the greater the spatial reuse. For this reason, spatial reuse is often employed as an evaluation metric for [4] scheduling algorithms. The next section describes the proposed strategy for scheduling transmissions in wireless networks under the SINR model.

III. The Proposed Scheduling Strategy

In this section we describe a scheduling strategy for wireless networks based on the SINR model. The strategy assumes that each device of set D of n devices knows its location on the two-dimensional Euclidean plane. After they communicate their positions to each other, devices can estimate the mutual interference caused by simultaneous transmissions. By computing the mutual interferences it becomes possible to determine which devices can transmit simultaneously so that communication occurs successfully. This strategy produces as output a TDMA scheduling for the transmitting devices.

The strategy starts with every device in the system broadcasting discovery messages carrying the unique identifier of the sender and its coordinates in the plane. Devices must use, at this first moment, some Medium Access Control (MAC) protocol that guarantees the eventual reception of the transmitted messages. As an example, a traditional protocol such as CSMA/CA (*Carrier Sense Multiple Access With Collision Avoidance*) [13] can be used.

Upon receiving a discovery message, a device stores the newly acquired information locally. After a predefined period of time after which no new discovery messages are received, all devices compute locally an M_{dist} distance matrix with dimensions $n \times n$, where n is the number of devices in the system. Each device is represented by its numeric, sequential identifier, thus $D = \{0, \ldots, n-1\}$. Each entry $M_{dist}[l, c]$ is also reference by $d_{l,c}$ and corresponds to the Euclidean distance between devices l and c.

The proposed strategy schedules transmissions for each and every device in the system. Each device is scheduled to a time slot. The schedule consists of a sequence of time slots. After the last time slot, all devices have had the opportunity to transmit and the schedule is executed again and this goes on indefinitely. The strategy is based on a heuristic designed to improve spatial reuse: each device only communicates with its closest device. Every device can detect the start of each time slot. The strategy assumes a dense one-hop network, in which all devices are within the transmission ranges of eachother. In the traditional wireless network models, only a single device of a one-hop network can communicate in each time slot. Thus, a schedule under those models requires n time slots for n devices. On the other hand, the SINR model allows spatial multiple simultaneous transmissions to be scheduled to a single time slot, as long as they respect the SINR threshold (described in the previous section). Observe that increasing the number of simultaneous transmissions has several advantages: including a reduction of the number of time slots needed for all devices to communicate, and also the time a device has to wait until it can communicate.

The transmission power level is individually adjusted for each transmission as shown below. In the SINR model, for a signal to be received correctly, the signal to noise plus interference ratio must be equal to or greater than the SINR threshold γ. Considering that there are no other simultaneous transmissions, it is possible to compute the minimum power level P_{Ti}, required by device i to communicate successfully with device j. The power level P_{Ti} is obtained from inequality 2 below.

$$\frac{\frac{P_{Ti}}{d(i,j)^{\alpha}}}{N_0} = \gamma \quad \therefore \quad P_{Ti} = \gamma + \cdot N_0 \cdot d(i,j)^{\alpha} \tag{2}$$

Notoriously, assigning the bare minimum power level to each transmitter makes it impossible for the system to have simultaneous transmissions, consequently not benefiting from spatial reuse. For simultaneous transmissions to be possible, the transmission power levels must be set so that the SINR condition at each receiver is above the limit (not *at* the limit), hereby called the spare SINR level, or γ_{spare}. In other words, a transmission power P_{Ti} is adopted for device i so that the resulting SINR at the receiver j in the absence of other transmissions is $\gamma + \gamma_{spare}$. Equation 3 shows how P_{Ti} is obtained.

$$\frac{\frac{P_{Ti}}{d(i,j)^{\alpha}}}{N_0} = \gamma + \gamma_{spare} \quad \therefore \quad P_{Ti} = (\gamma + \gamma_{spare}) \cdot N_0 \cdot d(i,j)^{\alpha} \tag{3}$$

The spare power makes spatial reuse possible, under certain conditions. Thus simultaneous transmissions between devices that are reasonably far apart are enabled, whenever the level of mutual interference is negligible. The amount of interference power P_{Φ} supported by the receiver j, when considering the reception of the signal transmitted by the device i, is given by:

$$P_{\Phi} \leq \frac{P_{Rj}}{\gamma} - N_0 \tag{4}$$

where P_{Rj} is the power level at the receiver j, given by $\frac{P_{Ti}}{d(i,j)^{\alpha}}$.

To improve the clarity of the presentation, the strategy is described applied for the example scenario shown in Figure 1. This scenario consists of 10 devices (with identifiers from 0 to 9) randomly distributed across the two-dimensional space.

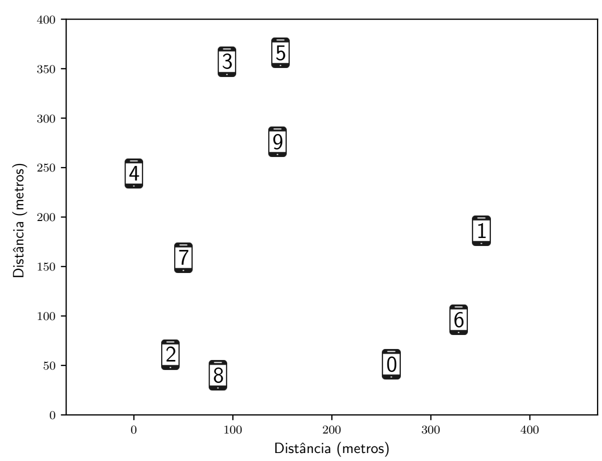

Fig. 1. An example scenario.

The proposed strategy identifies for each transmitter i which other devices can simultaneously transmit and still the communication from i to j is sucessful, i.e. received correctly by j. This set of devices that can communicate simultaneously with i is called β_i. Initially, for every device $k \in D$ – with the exception of i and j – it is checked whether a transmission by k to whatever is its closest device interferes with the reception of i's transmission at j. Thus the strategy checks how k's transmission is perceived by j, denoted by $P_{R(k,j)}$. If the interference is less than the level of interference supported by j, i.e. P_{Φ}, then k can transmit simultaneously with i. Thus $\forall k \in D - i | P_{R(k,j)} < P_{\Phi}$, k is included in the β_i set. Table I shows β_i for all devices of the example scenario.

TABLE I
THIS TABLE SHOWS THE DEVICES THAT CAN COMMNICATE SIMULTANEOUSLY WITH i.

Transmission	i	j	β_i
(0,6)	0	6	{3, 5}
(1,6)	1	6	{2, 4, 5, 8}
(2,8)	2	8	{1, 3, 5}
(3,5)	3	5	{0, 2, 6, 8}
(4,7)	4	7	{1, 6}
(5,3)	5	3	{0, 1, 2, 6, 8}
(6,0)	6	0	{3, 4, 5, 8}
(7,4)	7	4	{∅}
(8,2)	8	2	{1, 3, 5, 6}
(9,5)	9	5	{∅}

TABLE II
T_i IS THE LIST OF SETS OF DEVICES THAT CAN MAKE TRANSMISSIONS SIMULTANEOUSLY WITH DEVICE i.

Transmission	i	j	T_i
(0,6)	0	6	[{3}, {5}, {3, 5}]
(1,6)	1	6	[{2}, {4}, {5}, {8}, {2, 4}, {2, 5}, {8, 2}, {4, 5}, {8, 4}, {8, 5}, {2, 4, 5}, {8, 2, 4}, {8, 2, 5}, {8, 4, 5}, {8, 2, 4, 5}]
(2,8)	2	8	[{1}, {3}, {5}, {1, 3}, {1, 5}, {3, 5}]
(3,5)	3	5	[{0}, {2}, {6}, {8}, {0, 2}, {0, 6}, {0, 8}, {2, 6}, {8, 2}, {8, 6}, {0, 2, 6}, {0, 8, 2}, {0, 8, 6}, {8, 2, 6}, {0, 8, 2, 6}]
(4,7)	4	7	[{1}, {6}]
(5,3)	5	3	[{0}, {1}, {2}, {6}, {8}, {0, 2}, {0, 6}, {0, 8}, {1, 2}, {8, 1}, {2, 6}, {8, 2}, {8, 6}, {0, 2, 6}, {0, 8, 2}, {0, 8, 6}, {8, 1, 2}, {8, 2, 6}, {0, 8, 2, 6}]
(6,0)	6	0	[{3}, {4}, {5}, {8}, {3, 4}, {3, 5}, {8, 3}, {4, 5}, {8, 5}, {3, 4, 5}, {8, 3, 5}]
(7,4)	7	4	{∅}
(8,2)	8	2	[{1}, {3}, {5}, {6}, {1, 3}, {1, 5}, {3, 5}, {3, 6}, {5, 6}, {1, 3, 5}, {3, 5, 6}]
(9,5)	9	5	{∅}

Let $|\beta_i| = m$. The total number of non-repeating combinations between the elements (devices) of each set β_i is $2^m - 1$. That is, there are $2^m - 1$ possible combinations of distinct sets formed with the m devices that can transmit simultaneously with i. Now, it is necessary to check in which of these sets (i.e. combinations of simultaneous transmissions) the sum of the interferences at j is below the maximum limit P_Φ.

The first column of Table I shows the pairs of processes (i, j) that communicate according to the heuristics: each i communicates with the nearest device j. Thus, for example device 1 communicates with device 6, device 7 communicates with 4. The table also shows β_i, the set of those other devices that according to the computation described above can transmit simultaneously with i (to j). Thus the interference of a transmission of any device in β_i does not prevent the correct reception by j of the signal from i. Thus, for example, it is possible to schedule *individually* transmitters 2, 4, 5 or 8 simultaneously with device 1. As an example, in the case of device 7, no other simultaneous transmissions can be scheduled, that is, any other device that transmits simultaneously with device 7 causes such interference at device 4 that prevents it from successfully communicating with device 7.

In the next step, the algorithm investigates whether more than a single device can communicate simultaneously with i. The output of this step is a list of device sets T_i, each set has elements that can transmit simultaneously. Computing the sum of the interferences on j is below the maximum interference P_Φ allowed, so that j is still able to correctly receive the transmission from i. Initially T_i has m sets, each with an individual element of β_i. Next, the $m * (m - 1)$ two-by-two element combinations of β_i are checked. If any set of two elements of β_i are identified as possible simultaneous transmitters, that set is inserted into T_i. In the next step, for each of the sets of two elements in T_i, the other devices are checked to decide whether a third simultaneous transmission is possible. If a set of three possible simultaneous transmitters is identified, it is entered into T_i. The process repeats until it is concluded that either all the elements of β_i can transmit simultaneously, or when it is no longer possible to add any new sets to T_i. The result of this step for the example scenario is shown in Table II.

T_i is a list of sets of devices can make transmissions simultaneously with device i, in a way that does not compromise the reception of the signal at device j. However, there is no guarantee that the signals transmitted by the other devices in T_i are correctly received by their corresponding receivers. Therefore, it is necessary to verify the impact of the mutual interference on those devices. The next step does just that: for each set of each list $T_i, i = 0..(n-1)$ it checks whether the interferences allow *all* destination devices to successfully receive the corresponding signals correctly. The output of this step is the δ set list. The assessment is done as follows. Consider that for a given device i, T_i contains set $\{x, y\}$. For the three devices $\{i, x, y\}$ to transmit simultaneously, it is necessary that $\{i, y\} \in T_x$ *and* that $\{x, i\} \in T_y$. If this is true, the set $\{i, x, y\}$ is added to δ.

For the example scenario, the following δ list is produced: $[\{0,3\}, \{0,5\}, \{1,2\}, \{1,4\}, \{1,5\}, \{8,1\}, \{2,3\}, \{2,5\}, \{3,6\}, \{8,3\}, \{4,6\}, \{5,6\}, \{8,5\}, \{8,6\}, \{1,2,5\}, \{8,1,5\}, \{8,3,6\}, \{8,5,6\}]$. This list consists only of those sets of devices that can transmit simultaneously with guaranteed reception by all corresponding receiving devices. It is therefore possible to schedule all devices from any of the sets of δ to the same *time slot*.

Note that to build a schedule with spatial reuse it is not enough to simply select any sets in δ in any order and assign each set to some *time slot*. Note that if that is done, the same device can be in multiple sets and thus assigned to multiple slots. This is not allowed: each device is scheduled only once. Thus, when a set of devices is scheduled for a given *time slot*, other sets containing those devices that have already been scheduled cannot be scheduled again. Therefore, it is necessary to properly choose which sets to schedule in order to obtain a schedule that is efficient overall, in particular in terms of spatial reuse.

In the next step of the proposed strategy, undirected graph $G_\delta = (V, E)$ is built from list δ. Each vertex $v \in V$ represents

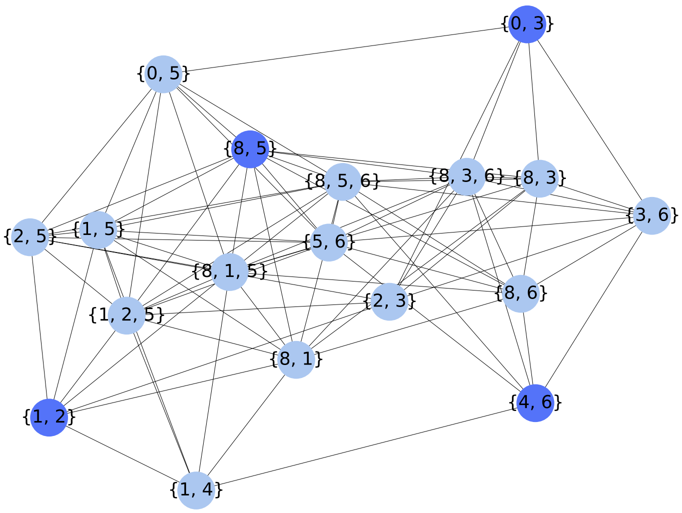

Fig. 2. Graph G_δ computed for the example scenario.

a set contained in δ. There is an edge $(u, v) \in E$ only if both u and v have at least a device in common. An algorithm (such as the one in [14]) is executed to find the largest independent vertex set of G_δ. An independent set of vertices S of a graph G is such that S does not contain any vertices that are adjacent in G. Thus for the scheduling problem, selecting a set of vertices S guarantees that the same vertex (device) is selected at most only once. As the objective is to take advantage of spatial reuse to minimize the size of the schedule, the largest independent vertex set allows exactly that. Each vertex of S selected by the algorithm has its set of devices scheduled to transmit simultaneously in the same time slot. Devices that remain not scheduled up to this point, must be assigned to individual *time slots*, this is done following the ascending order of their identifiers. Table III shows the schedule produced by the proposed strategy for the example scenario. Figure 2 shows in darker blue the largest independent vertex set for the example scenario. Note that devices 7 and 9 are scheduled later.

TABLE III
THE FINAL SCHEDULE.

Time Slot	i
0	{0,3}
1	{1,2}
2	{4,6}
3	{5,8}
4	{7}
5	{9}

IV. EVALUATION

The strategy presented in Section III was evaluated through simulation. A wireless communication network simulator under the SINR model was implemented using OMNeT++[1] and its Inet Framework[2]. From the execution of several experiments, we sought to evaluate the ability of the algorithm to efficiently schedule the devices in networks with different densities. In all scenarios, systems consisted of 10 devices randomly distributed across the two-dimensional plane, according to the density level specified for each scenario. Scenarios with $10m \times 10m$, $25m \times 25m$, $50m \times 50m$ and $100m \times 100m$ were used, for each of these scenarios 6000 different placements of the devices were considered. A baseline for comparisons was defined considering a traditional schedule for such scenarios, which always consists of 10 time slots: a single device can communicate in each slot. Spatial reuse is the evaluation metric of choice. The greater the spatial reuse, the smaller the number of slots needed.

Figure 3 shows for the different network densities, the respective percentages of the sizes of the schedules obtained. In scenarios where the devices are all very close to each other, that is, in scenarios of higher density, spatial reuse reduces. This is expected, as the interference among multiple communications increases with the density. Note in Figure 3, that the densest scenario ($10m \times 10m$) resulted in the highest percentage of schedules requiring 10 time slots: 23.9% of the simulated scenarios. This percentage drops to 15% in the $25m \times 25m$ cenarios, and then to 13.5% in the $50m \times 50m$ scenarios, but the reduction for scenarios that are even more sparse is now minimal, getting to 13.4% in the $100m \times 100m$ scenario.

On the other hand, in the scenario of $100m \times 100m$, 23% of the experiments resulted in schedules with 5 or 6 slots. This can be considered a very efficient schedule, which reduces by 50% the number of *time slots* in comparison with the *baseline*. When the density doubles, as the area is reduced to $50m \times 50m$, the percentage of schedules obtained with 5 or 6 slots increases to almost 25%. In the scenario with area $25m \times 25m$ this percentage remains similar, just below 22%. Interestingly, in all scenarios about a third of the schedules required 7 time slots, a reduction of about 30% in comparison with the baseline.

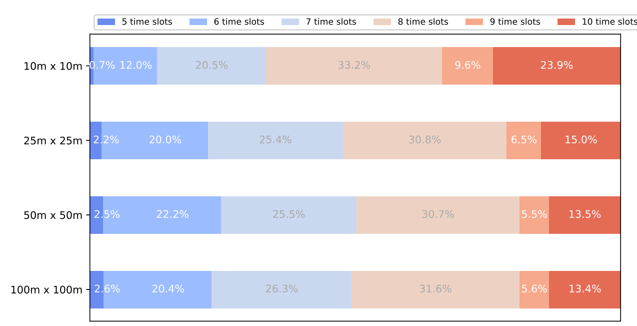

Fig. 3. Scheduling in networks of different densities.

If we take into account schedules with between 5 and 7 *slots*, in the less dense scenario with area $100m \times 100m$, the percentage of those schedules was of 49.3%. The value increases to 50.2% when the area is halved to $50m \times 50m$.

[1] https://omnetpp.org/
[2] https://inet.omnetpp.org/

Increasing (doubling) the density further to $25m \times 25m$ results in a similar value, with about 47% of the schedules with between 5 and 7 *slots*. In the smallest (and densest) area ($10m \times 10m$) the percentage drops to 33.2%. In this case, it is clearer that the interference starts to make spatial reuse more difficult.

However, a result that can be considered surprising is that the differences of the sizes of the schedules obtained by the strategy for the different scenarios are not really very significant. Figure 4 also shows the percentages of schedule sizes, but this time ignoring placements that do not allow simultaneous transmissions; in other words, results are presented only for scenarios that allow at least a pair of simultaneous transmissions.

Figure 4 shows that for the scenarios of $100m \times 100m$, $50m \times 50m$ and $25m \times 25m$ the percentages of schedules with 5 to 9 slots are quite similar, the differences are of at most 1%, often even less. The percentages change slightly more as the densest scenarios ($10m \times 10m$) are considered. Comparing the most with the least dense scenario ($100m \times 100m$), the percentage of schedules with 5 *slots* increases from 0.9% to 3% while the schedules with 9 slots decrease from 12, 7% to 6.5

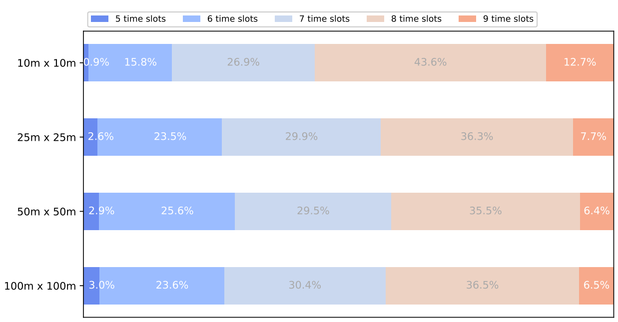

Fig. 4. Scheduling in different densities, considering only scenarios that allowed simultaneous transmissions.

Overall, the results make it clear that the strategy is effective, that it can be used in wireless communication networks of different densities, defining efficient schedules with spatial reuse.

V. Conclusion

This work presented a scheduling strategy for wireless networks under the SINR model. The strategy assumes a 1-hop network in which devices know their positions on the plane and are capable of estimating interference levels of mutual transmissions. The strategy uses a heuristic whereby each device communicates only with the other device that is closest to itself. The strategy allows multiple devices to transmit simultaneously, given all the respective receivers are able correctly receive and decode the received signals.

The strategy was evaluated through simulation, and the results indicate its effectiveness in terms of spatial reuse for networks of different densities. It is noteworthy that efficient strategies for communication in dense networks are increasingly important, as new technologies such as 5G require increasing density.

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