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NEW CONCEPTS FOR A DECENTRALIZED, SELF-ORGANIZING AIR-TO-AIR RADIO LINK

Michael Walter, Nico Franzen, and Michael Schnell
German Aerospace Center (DLR), Wessling, Germany

Abstract

In this paper, a new access scheme for an aeronautical mobile ad-hoc network (MANET) is presented. The access scheme combines the ideas of nested cellular reuse patterns and variable guard times. The nested cellular reuse patterns solve the hidden station and the near-far problem whereas variable guard times ensure the efficiency of this particular access scheme. Conventional approaches for coordinated, consecutive transmissions require fixed guard times. Considering aeronautical MANETs with their large dimensions together with typical aeronautical applications having short message durations, fixed guard times are inefficient, since the ratio between massage duration and guard time becomes too small. An algorithm for calculating the variable guard times in a MANET is presented and a lower bound for the mean required guard time is derived. In addition, the question of message collisions that might influence the stability of the algorithm is addressed.

1. Introduction

For today's civil aviation aircraft several digital radio communication standards are already available and more are about to be developed. Yet, in the current ATM system, only very limited attention is given to direct air-to-air (A/A) data communications, with most services operating between aircraft and ground stations (A/G). Already existing systems making use of A/A communication include, e.g., Traffic Alert and Collision Avoidance System (TCAS) and Automatic Dependent Surveillance – Broadcast (ADS-B).

Beside the surveillance and collision avoidance systems mentioned above, it is desirable for future applications to have an addressed air-to-air link as well [1]. When looking at access schemes for aeronautical MANETs, one finds that the efficiency of such access schemes can be greatly improved by using the position information of the participating aeronautical nodes [2]. However, due to the large radio horizon of the aeronautical nodes, it is expected that each node needs to know the position information of the surrounding nodes from a large area to let the access scheme benefit from this information. In densely populated airspace it is unclear, if this can be achieved with the existing surveillance links based on the ALOHA protocol [3]. The focus of this paper is to develop an efficient coordinated access scheme for an aeronautical MANET mainly intended for a high number of short messages. One of the problems of coordinated access schemes like FDMA (Frequency-Division Multiple-Access) and TDMA (Time-Division Multiple-Access) is that there is always some kind of guard needed to protect the own transmission from the transmissions by others. For TDMA systems for example a guard time is needed to compensate for the propagation time of the transmitted signal.

The problem that arises for aeronautical applications is that fixed guard times would be very large. For example, consider two aircraft flying at FL 360 at a distance of 400 nmi, i.e. within their mutual radio horizon. This would correspond to a required fixed guard time of around 2.5 ms which is much larger than the guard times used in terrestrial networks. For a message length like that of the Universal Access Transceiver (UAT) of 280 μs this would mean that the guard time is considerably longer than the actual message. Therefore, more efficient guard time schemes have to be used in order to increase the efficiency of the coordinated access.

One approach to solve this problem is discussed in [4,5]. There, the guard times are reduced by finding the shortest path that connects all nodes with each other. One of the algorithms that solve this particular problem is for example described in [6]. Another problem for an aeronautical network is the dynamic behavior. To make the transmission schedules immune to topology changes, [7] proposes Galois fields to calculate the transmission schedules and guarantee a collision-free reception. This scheme won't be practical though, because in an aeronautical network, the transmissions of one aircraft may interfere with the reception of other messages at any other aircraft within the radio horizon. Due to the extremely large area covered by the radio horizon and the relatively small attenuation of free space propagation, many more other terminals would have to be considered as neighbors of a terminal than in terrestrial networks.

The coordinated MANET access scheme which is proposed in this paper relies on two concepts. The first one is the introduction of cells, geographical areas in which a certain channel will be used by all aircraft. The second concept is the introduction of variable guard times as already mentioned above for the sharing of one channel among all terminals within a cell. In Section 2 of this paper, the cellular reuse pattern of the network is explained and it is shown how such a pattern can be constructed in an innovative way in order to avoid common MANET problems. Section 3 recapitulates the idea of variable guard times from [4,5], describes a way of how to calculate such guard times in a distributed network and presents simulation results on the expected relative savings. A lower bound for the mean required guard time is derived as well. Section 4 gives an initial assessment of the impact of errors in the calculation of the variable guard times. Finally, conclusions are drawn in Section 5.

2. Nested Cellular Reuse Patterns

In the development of a Medium-Access (MAC) scheme suitable for a MANET, several challenges have to be overcome which are specific to the distributed nature of the network and do not appear in centralized networks where channel access is organized, e.g. by a base station. The most important and common issues include the near-far problem, the hidden terminal problem, as well as the difficulty of receiving one channel while transmitting on another channel. The near-far problem describes the fact that in a distributed network, it is not possible to use power control to ensure that all transmissions arrive at a receiver with approximately the same power, as there are multiple receivers at different locations. Thus, the transmissions of a station close to a receiver and of another, far away station will arrive at the receiver with a substantial difference in power. The hidden terminal issue arises when trying to coordinate medium access such that no conflicting transmissions occur. In order to do this perfectly, a transmitter would typically have to coordinate its transmission with other transmitters situated outside of its own communication range. Without further measures, this will not be possible and a certain probability of conflicting transmissions from hidden terminals remains. One notable possibility to reduce the number of hidden terminals in a network is to propagate coordination messages over multiple hops. A similar solution is the use of Request-to-Send / Clear-to-Send messages as in the widely used IEEE 802.11 standard for wireless networks. However, both incur overhead and the latter is obviously unsuitable for broadcast messaging.

To solve the hidden terminal problem, we propose the use of an access scheme based on cells in an aeronautical MANET. Such a scheme would span the globe with a map of network cells, and the radio channel used by a terminal for its transmissions would depend on the cell the terminal is currently located in. This way, conflicts between transmissions from terminals in different cells may be completely avoided, while it can be ensured that all terminals within the same cell are in mutual radio range and are therefore able to coordinate their transmissions. Such a cell-based approach has already been proposed in [8] for a MANET between trains. While a cell-based access scheme requires each terminal to know its current location on earth, it is important to note that relatively large errors in this position information can be tolerated if transitory regions are designed around the cell borders. A terminal within the transitory region would be allowed to connect to any of the adjacent cells.

The two-dimensional map of MANET cells could be composed of simple, hexagonal cells as depicted in Figure 1. As the cells are only "virtual", i.e. they are not bound to any kind of infrastructure like base stations, no complicated deviations from the hexagonal cell shape are necessary like in a conventional cellular network with base stations. As already mentioned, each cell would be assigned a radio channel and a reuse pattern would be necessary to limit the number of necessary channels. Figure 1 shows such a pattern with $N_{\text{cell}} = 7$ different cells (channels), denoted by the letters A to G. It can be described by the relative positioning of cells of the same kind, given by the numbers i and j [9]. These coordinates count the number of cells i one needs to go in a first direction and the number of cells j one needs to go in a second direction after making a 60° turn to the left, in order to get from one cell to the next cell of the same kind, as apparent from Figure 1. The total size of the reuse pattern is [9]

$$N_{\text{cell}} = i^2 + j^2 + ij \,. \tag{1}$$

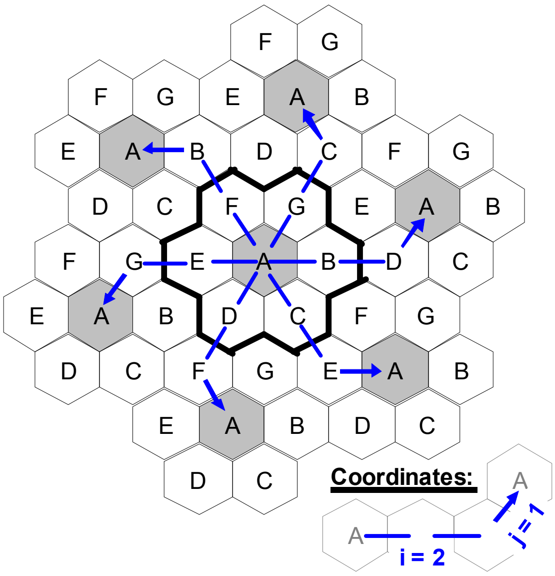

Figure 1: Cell Scheme Basics.

After assigning a fixed block of physical resources (channel) to each cell, these resources need to be shared dynamically among the terminals within the cell. In this paper, it is assumed that an additional TDMA scheme is used for that purpose, regardless of how the channel itself is constructed. The TDMA scheme implies that the terminals in the cell transmit consecutively in time and apply an appropriate distributed coordination algorithm.

While a cell-based access scheme can help to solve the hidden terminal problem, the other issues initially mentioned still exist. Consider three terminals TA1, TA2 and TB1 located in two different cells A and B with respective channels A and B as depicted in Figure 2. Assume that TA1, located at the edge of cell A, is receiving a transmission on channel A from TA2 located diagonally across the cell, and note that TB1 is located directly next to TA1 in the adjacent cell B. TA1 must be able to correctly receive the transmission of TA2, as without correct reception of all transmissions from the same cell, the hidden terminal problem would not be solved. In the presence of another transmission from TB1, the near-far problem arises for the reception of TA2 by TA1. What's more, in a MANET the aim is to enable any terminal to receive all other terminals in a certain surrounding, e.g. within a certain minimum distance, regardless of virtual cell boundaries. Therefore, TA1 also needs to correctly receive any transmission of TB1 on channel B. This holds even if TA1 itself is transmitting on channel A.

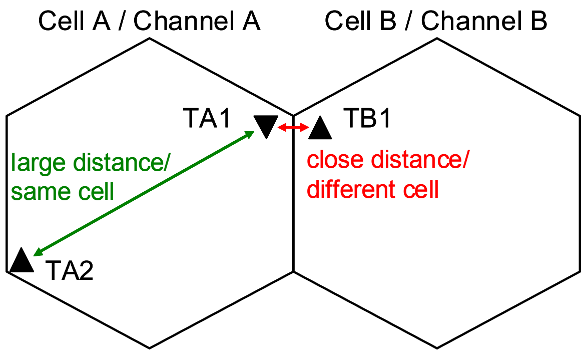

Figure 2: Problematical Terminal Locations for a MANET Cell Scheme.

As a conclusion, adjacent cells need to be assigned channels with extremely low inter-channel interference, such that reception on one channel is not hindered by transmitting on the other. Note that once this is fulfilled, the near-far problem is solved as well in the scenario considered herein, as the "near" and "far" terminals would be transmitting on different, highly isolated channels. Multiple-access schemes providing such high channel isolation are for example FDMA with substantial guard bands between the channels, as is commonly used for full-duplex transmission on two different frequencies in centralized networks, or TDMA. In the remainder of this section, we will assume TDMA whenever an access scheme with substantial channel isolation is necessary.

One problem with access schemes providing substantial channel isolation is that they tend to be less efficient than access schemes with moderate channel isolation (e.g. FDMA with small guard bands between channels). In case of FDMA with substantial guard bands, this is immediately apparent from the size of the necessary guard bands. For TDMA, one has to take a closer look for realizing that fact. As stated before, terminals within the cells dynamically share their channel by TDMA. Without the use of variable guard times, this requires a map of timeslots with guard intervals corresponding to the propagation delay of a signal travelling diagonally across the cell. In an aeronautical MANET with cell diameters of, e.g., 150 nmi, this corresponds to a fixed guard interval of roughly 1 ms. Note that 150 nmi is the largest range requirement for air-to-air surveillance to be found in the COCR [1]. Applying TDMA also to separate the N_{cell} channels necessary to establish the reuse pattern means that N_{cell} sections of equal length in a recurring framing structure are required, with each section containing the timeslots for one of the N_{cell} channels. To make a simple example, let us assume that there are $N_{\text{cell}} = 16$ channels and with that a reuse pattern of equal size. Furthermore, assume that each cell has a diameter of 150 nmi and there are 100 terminals in each cell, each terminal transmitting one message per frame. This would require 100 timeslots per channel (cell) per frame. As all the different cells transmit consecutively, 1600 timeslots would be needed in a frame. The accumulated guard time in one frame would amount to 1.6 seconds. If the messages transmitted in the network are mostly short messages, this will lead to a huge loss in efficiency. What's more, due to the accumulated guard times, the network won't be able to provide update delays of less than 1.6 seconds no matter how much bandwidth is provided for the network.

The previous considerations demonstrate that it would be beneficial to combine an access scheme with substantial channel isolation with a second access scheme into the same reuse pattern. The second access scheme would have to allow channels to transmit concurrently and to operate more resource efficient, while it would not have to provide very high channel isolation. The additional use of this second access scheme would then limit the inefficiencies of the first access scheme, while the requirement for adjacent cells to be assigned channels with extremely low inter-channel interference could still be fulfilled. Also, consider that different access schemes for the construction of the needed channels may be nested arbitrarily. As an example, 4 channels separated in a frame by TDMA may be further subdivided by 4 FDMA or CDMA channels, yielding 16 channels in total as depicted in Figure 3.

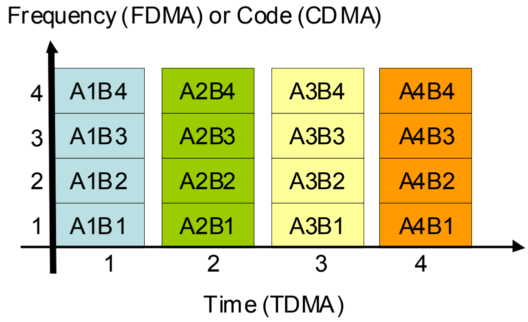

Figure 3: Nesting of Two Access Schemes.

What might be less obvious is that reuse patterns may be nested arbitrarily as well. In order to do this, one establishes a first reuse pattern, in the following called pattern A or outer pattern. Figure 4a exemplifies such a pattern for $i_A = 2$, $j_A = 0$ and the resulting size of $N_A = 4$ cells. Next, one looks at all cells of the first type A1 and realizes the possibility to put a second reuse pattern into those cells. This is shown in Figure 4b and the second pattern will be referred to in the following as pattern B or inner pattern. The same procedure is possible with all other cell types of the outer pattern A, resulting in pattern C depicted in Figure 4c where B is completely nested in A. The nested pattern is of size $N_{\text{cell}} = N_C = N_A \cdot N_B$ and it may be seen from Figure 4 that $i_C = 4$, $j_C = 0$. By geometrical considerations, one finds that for the nesting of two patterns A and B, the reuse coordinates of the resulting pattern C are in general given by the following equations

$$\begin{aligned} i &= i_B i_A - j_B j_A \ , \\ j &= i_B j_A + j_B (i_A + j_A) \ . \end{aligned} \tag{2}$$

If $i > 0$

$$\begin{aligned} i_C &= i \ , \\ j_C &= j \ , \end{aligned} \tag{3}$$

otherwise

$$\begin{aligned} i_C &= j + i \ , \\ j_C &= -i \ . \end{aligned} \tag{4}$$

Note that the above may be extended to the nesting of more than two patterns in a straightforward way, as a third pattern can be nested into pattern C and so on. For k reuse patterns of sizes N_1 to N_k, the total size of the nested pattern would be

$$N_{\text{cell}} = \prod_{m=1}^{k} N_m . \qquad (5)$$

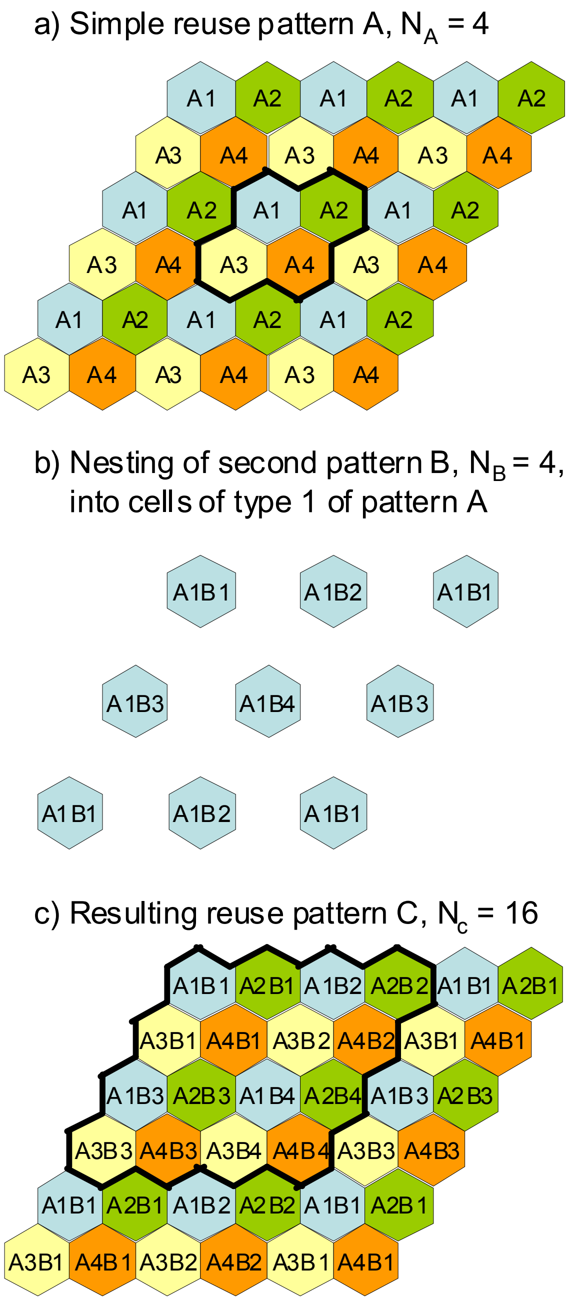

Figure 4: Nesting of Two Reuse Patterns.

Each level m of nesting could use a different access scheme if necessary. However, as the purpose of nesting in this paper, namely the combination of two access schemes with properties as described before, may be fulfilled by a nesting depth of only 2, we go back to the example given by Figure 4c. What remains to be done is the assignment of channels to cells in the resulting pattern C. To do this, channels differing in time (TDMA), i.e. in the time section of a frame that contains their slots, are associated with different cells of the outer scheme A, while different cells of the inner scheme B are associated with channels of different frequency (FDMA) or code (CDMA). For a better understanding, the cells in Figure 4c and the channels in Figure 3 are named according to this rule. As can be seen, terminals in adjacent cells will in this way never transmit at the same time, solving the problem of concurrent transmission and reception and also the near-far problem. Furthermore, always 4 of the 16 channels are active at the same time, which means that also the guard intervals of the slots in those channels coincide in time. This reduces the accumulated guard time per frame fourfold, from 1.6 seconds to only 400 ms in the previously made, simplified example with 100 slots per channel and frame. Note that the access scheme for the inner pattern B would not have to provide substantial channel isolation. If for example FDMA is used, the guard bands could be small. As 400 ms of accumulated guard time per frame is still a lot in a network with many short messages, the next section investigates a method in which guard times may be further reduced.

3. Variable Guard Times

A nested cell scheme using e.g. a combination of TDMA and FDMA as described in Section 2 already solves important MANET issues. This section focuses on how the channel of a cell is dynamically shared among the terminals within the cell. As already mentioned in Section 2, a distributed coordination algorithm is required for this, and we assume that the individual terminals access the channel consecutively in time. Conventionally, time slots with fixed guard times would be used to implement this TDMA component. Due to the large size of the cells in an aeronautical scenario, however, the guard times become very long and the access scheme therefore inefficient for short messages.

In line with Section 2, cell diameters of 150 nmi are assumed herein, which corresponds to guard times of roughly $t_G = 1$ ms. In order to accommodate as many messages as possible per unit time in one cell, and thus as many terminals as possible, the bandwidth of the system could be increased to reduce the duration of a message. But with these long guard times, the efficiency is reduced as can be seen from Eq. (6), where the efficiency is defined as

$$\eta = \frac{N_M}{B(t_M + t_G)} \tag{6}$$

with N_M the message length (e.g. the amount of information bits contained in the message), B the bandwidth, and t_M the message duration.

A higher efficiency with a shorter message length can be attained, if the guard times are reduced. But the guard times are needed to compensate for the transmission delay in the network. For fixed guard times, or traditional timeslots as depicted in Figure 5, a worst case assumption of the transmission delay is made, i.e. the diameter of the cell is taken for all transmissions. This, however, is not needed, since the next scheduled transmitter can send its message as soon as the previous message has arrived to ensure that there will be no collision [5].

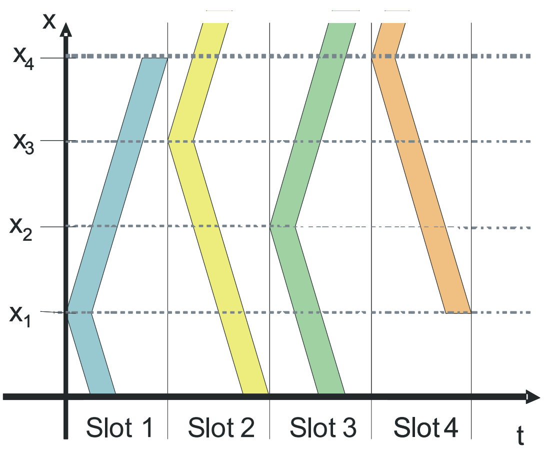

Figure 5: Inefficient Tx Schedule Due to Fixed Slots.

In order to reduce the guard times, they will be made variable so that the next scheduled transmitter can send as soon as it has received the message and does not have to wait like when using fixed guard times. As shown in Figure 6, the efficiency will be increased, since all of the transmitters can broadcast their message earlier and more messages will fit in one frame.

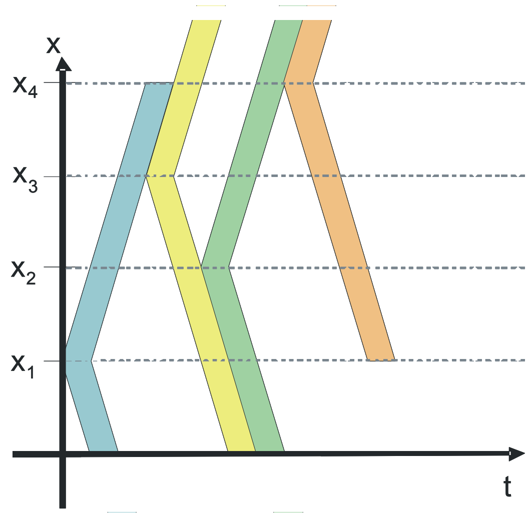

Figure 6: Removal of Unnecessary Guard Times.

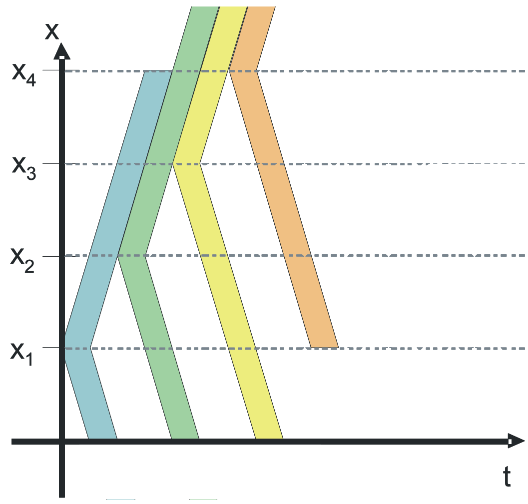

Figure 7: Rescheduling of Transmission to Obtain Optimal Schedule.

The transmission schedule, however, is still not optimal. The goal has to be to minimize the time between two successive transmissions. The transmission stations X_1 to X_4 for example could be permuted in a way that they transmit their messages in the order shown in Figure 7. It shows that the ideal schedule for the one-dimensional case is simply the next neighbor on the vertical axis. It gets more complicated though, if two- or three-dimensional aircraft distributions are considered. To minimize the guard times in one cell, the global round-trip distance, if every aircraft is visited once, has to be minimized. This corresponds to a well known problem in computer science called the (symmetric) travelling salesman problem (TSP). It is symmetric, since all aircraft are assumed to have a two-way radio connection between each other in one cell.

A lot of research has been done in this field and there exist many algorithms, which solve this particular problem. For this paper, the Concord solver was used to solve the travelling salesman problem [10]. An example of the solution of the Concorde solver with aircraft uniformly distributed in a 100 nmi x 100 nmi two-dimensional cell is shown in Figure 8, where start and end point of the algorithm can be seen in the upper right part of the figure. In order to obtain a solution the Euclidean metric is used for distance calculation, i.e. the triangle inequality is valid and the direct path is always the shortest. Note, we assume a Poisson distribution for all aircraft on a global scale. Thus, the positions of all aircraft within a cell are independent and uniformly distributed.

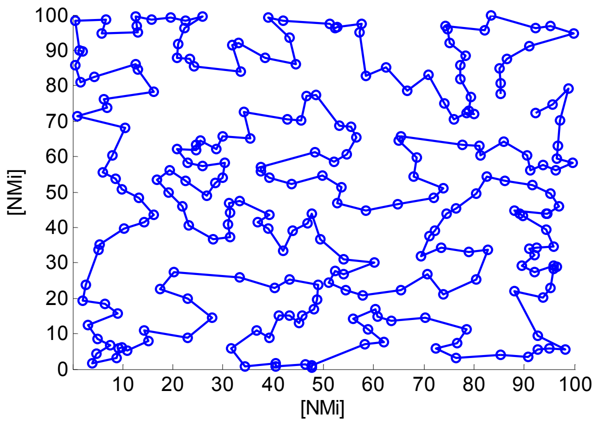

Figure 8: Shortest Path Connecting all Aircraft.

Since the travelling salesman problem is an NP-hard problem, no algorithm is known to solve it optimally in polynomial time. The algorithm that is used in this paper is a heuristic algorithm, which solves the problem faster, but is not necessarily optimal. The algorithms and the computing power of today make it possible that each aircraft could calculate the schedule according to the GPS positions of all the aircraft in one cell on its own and thus determine the transmission schedule. The GPS time will also be used to synchronize the transmissions of all aircraft. The position update for the travelling salesman problem will be sent once per second. The frame starts every full second and each aircraft determines its transmission time in the frame according to the result of the travelling salesman algorithm. The frame itself will be composed of a number of message start opportunities (MSO) like in the UAT frame. They are used to discretize the starting points of the aircraft's transmissions. The aircraft will transmit its coordinates in the MSO that corresponds to the correct offset from the start of the frame. Another possibility of determining the next scheduled transmission would be token passing, but it would fail, if an aircraft misses its transmission opportunity. With MSOs, the next aircraft will send its transmission anyway, because it calculated the transmission schedule on its own and does not depend on receiving the previous transmission. The disadvantage of this access scheme is, however, that data collisions can occur, if the aircraft have different databases and calculate different routes in the travelling salesman algorithm. This drawback will be discussed later.

As said before, conventional guard times depend on the maximum distance between two points within the same cell. In the following, this distance will be referred to as the cell diameter, denoted by $d_{\max}$. For reasons of simplicity, this section of the paper considers quadratic or cubic cells when looking at the two-dimensional or three-dimensional case, respectively. Therefore, the cell diameter is given by $d_{\max} = l_{\text{cell}}\sqrt{n}$, where l_{cell} is the edge length of a cell and n is the dimensionality.

For a fair comparison the total guard times per frame of both the variable and fixed case will be considered in this paper. For the fixed guard time case, the total guard time $T_{G,\text{fix}}$ is given by

$$T_{G,\text{fix}} = \sum_{i=1}^{N} \frac{d_{\max}}{c} = N\frac{d_{\max}}{c}, \qquad (7)$$

where N is the number of aircraft (slots per frame) and c the speed of light. The total guard time $T_{G,\text{var}}$ in the case of variable guard times depends on the path lengths $d_{i,(i+1)\bmod N}^{\text{TSP}}$, $i = 1,\ldots,N$, between two adjacent aircraft i and $i+1$ that are connected by the graph created by the TSP algorithm. The total guard time is therefore the solution of the TSP algorithm divided by c

$$T_{G,\text{var}} = \sum_{i=1}^{N} \frac{d_{i,(i+1)\bmod N}^{\text{TSP}}}{c}. \qquad (8)$$

Since $d_{i,j}^{\mathrm{TSP}} \le d_{\max}$, the total guard time for the variable guard time case is upper-bounded by the fixed case $T_{G,\mathrm{var}} \le T_{G,\mathrm{fix}}$. Of special interest is the mean ratio S^{TSP} between total variable and total fixed guard time, since it is a good measure for the guard time saving obtained by variable guard times. It is determined as the expected value

$$S^{\mathrm{TSP}} = E\left\{\frac{T_{G,\mathrm{var}}}{T_{G,\mathrm{fix}}}\right\} = \frac{1}{d_{\max}} E\left\{\frac{1}{N}\sum_{i=1}^{N} d_{i,(i+1)\,\mathrm{mod}\,N}^{\mathrm{TSP}}\right\} \quad (9)$$

which is calculated on the basis of a large number of different aircraft constellations following a Poisson distribution for which the TSP algorithm is applied.

The assumption of Poisson distributed aircraft can be seen as a worst case scenario, since the en-route aircraft are flying on airways, e.g. the North Atlantic Tracks between North America and Europe. There, all aircraft move in a certain corridor provided by the air traffic controller and the pattern of the aircraft looks much more regular and clustered. The results should therefore provide only an indication of what guard time savings can be achieved, if the guard times are made variable.

In the following, a lower bound S for the mean ratio between total variable and total fixed guard time is determined. As will be shown, the aircraft density is an important parameter for this lower bound. With increasing aircraft density the variable guard times become smaller, since the mean distance between aircraft decreases. For calculating the lower bound S, the expected value $E\{D\}$ of the distance D to the nearest aircraft is required. First, the probability that there is no aircraft within a radius r is determined. The Poisson distribution of aircraft leads to the following result for the two-dimensional case

$$P(D \ge r) = \exp(-\pi r^2 \rho), \quad (10)$$

where ρ is the aircraft density in aircraft per unit area. The probability that there are one or more aircraft within the radius r thus is given by

$$P(D < r) = 1 - \exp(-\pi r^2 \rho). \quad (11)$$

For calculating the expected value of the distance D, the probability density function p is calculated as

$$p(D < r) = \frac{dP}{dr} = 2\pi r \rho \exp(-\pi r^2 \rho). \quad (12)$$

With the probability density function p, the expected value $E\{D\}$ of the distance to the nearest aircraft is

$$E\{D\} = \int_0^\infty 2\pi r^2 \rho \exp(-\pi r^2 \rho)\, dr = \frac{1}{2\sqrt{\rho}}. \quad (13)$$

This result is used to derive the lower bound S for the mean ratio between total variable and total fixed guard time as defined by S^{TSP}. Consider that on the path found by the TSP algorithm, even in case of an optimal solution, the distance between one aircraft and the next can never be smaller than the distance D to the closest aircraft. Hence, for the expected value $E\{D\}$ holds

$$E\{D\} \le E\left\{\frac{1}{N}\sum_{i=1}^{N} d_{i,(i+1)\,\mathrm{mod}\,N}^{\mathrm{TSP}}\right\}. \quad (14)$$

Using Eq. (14) together with Eq. (9) the lower bound S can be established as

$$S = \frac{E\{D\}}{d_{\max}} \le S^{\mathrm{TSP}}. \quad (15)$$

Noting that $d_{\max} = l_{\mathrm{cell}}\sqrt{2}$ for the two-dimensional case and using Eq. (13), finally gives

$$S = \frac{1}{2 l_{\mathrm{cell}} \sqrt{2\rho}}. \quad (16)$$

Alternatively, Eq. (16) may be expressed in terms of the expected number of aircraft within one cell. For a Poisson distribution, $E\{N\} = \rho V_{\mathrm{cell}}$ holds, where $V_{\mathrm{cell}} = l_{\mathrm{cell}}^n$ is the volume of an n-dimensional cell. For $n=2$, this leads to

$$S = \frac{1}{2\sqrt{2E\{N\}}}. \quad (17)$$

Figure 9 shows this theoretical lower bound S together with S^{TSP} as simulated using the TSP algorithm. As can be seen, the guard time is significantly reduced in the mean. Most importantly, both S and S^{TSP} decrease with increasing aircraft density, as the necessary variable guard times decrease with increasing aircraft density, whereas fixed guard times stay constant. For 100 aircraft the mean ratio between total variable and total fixed guard time S^{TSP} is only around 5.5 % according to the TSP simulations.

Figure 9 also shows that the gap between the theoretical lower bound and the simulated curve is small, although a heuristic algorithm is used. That means that the algorithm performs well and is not far from the optimal solution. There is no need to increase the complexity for a more sophisticated algorithm and gain only a fraction of a percent reduction in guard times.

Next, the three-dimensional case will be considered. The theoretical results will be provided for the *n*-dimensional case, since we wanted to keep the derivation of the formula general.

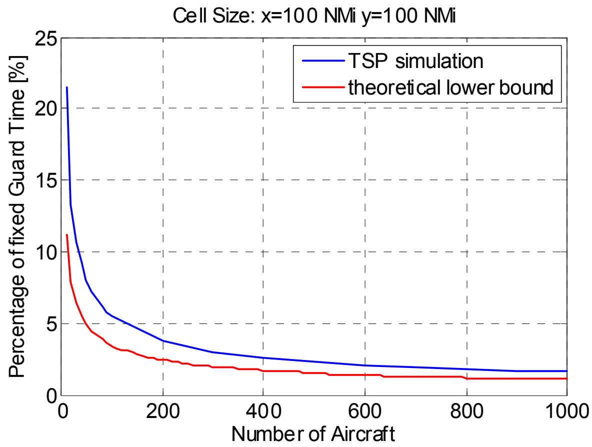

Figure 9: Saving of Guard Time in 2-D Case.

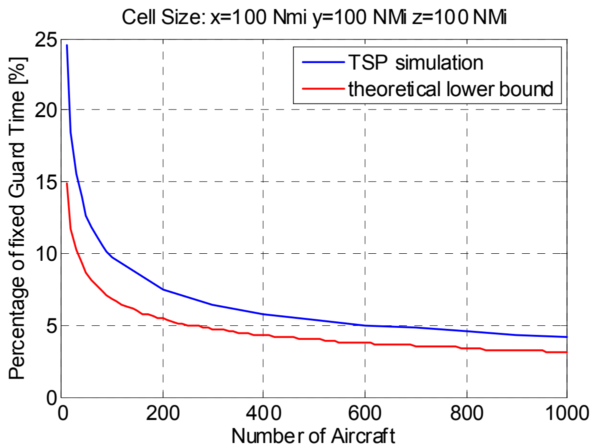

Figure 10: Saving of Guard Time in 3-D Case.

For determining the probability that there is no aircraft within a radius *r*, the volume of the *n*-dimensional sphere is needed. It is given by

$$V = \frac{\pi^{n/2}}{\Gamma\left(\frac{n}{2}+1\right)} r^n = a(n) r^n , \qquad (18)$$

where Γ is the gamma function and *a(n)* a factor that depends on the dimension *n*, but not on the radius *r*. The probability that there is no aircraft within an *n*-dimensional sphere thus becomes

$$P(D \geq r) = \exp(-a(n) r^n \rho) . \qquad (19)$$

The probability density function *p* for $D < r$ therefore results in

$$p(D < r) = n r^{n-1} a(n) \rho \exp(-a(n) r^n \rho) . \qquad (20)$$

With the probability density function *p*, the expected value $E\{D\}$ of the distance to the nearest aircraft for arbitrary *n* is given by

$$\begin{aligned} E\{D\} &= \int_0^\infty n r^n a(n) \rho \exp(-a(n) r^n \rho) dr \\ &= \frac{1}{\sqrt[n]{a(n)\rho}} \frac{1}{n} \Gamma\left(\frac{1}{n}\right) \qquad (21) \\ &= \frac{1}{n\sqrt{\pi}\sqrt[n]{\rho}} \Gamma\left(\frac{1}{n}\right) \sqrt[n]{\Gamma\left(\frac{n}{2}+1\right)} . \end{aligned}$$

Substituting $E\{D\}$ in Eq. (15) with the result of Eq. (21) and using again $d_{\max} = l_{\mathrm{cell}} \sqrt{n}$ as well as $\rho = E\{N\} / V_{\mathrm{cell}}$ with $V_{\mathrm{cell}} = l_{\mathrm{cell}}^n$ finally gives the lower bound *S* for the mean ratio between total variable and total fixed guard time for the *n*-dimensional case

$$S = \frac{\Gamma\left(\frac{1}{n}\right)}{n\sqrt{n\pi}} \sqrt[n]{\frac{\Gamma\left(\frac{n}{2}+1\right)}{E\{N\}}} \qquad (22)$$

which for the three-dimensional case simplifies to

$$S = \frac{\Gamma\left(\frac{1}{3}\right)}{3\sqrt{3\pi}} \sqrt[3]{\frac{\Gamma\left(\frac{5}{2}\right)}{E\{N\}}} \approx \frac{0.32}{\sqrt[3]{E\{N\}}} . \qquad (23)$$

Figure 10 shows that the mean ratio between total variable and total fixed guard time for the three-dimensional case is increased compared to the two-dimensional case. Nevertheless, the saving compared to fixed guard times is still enormous. For an aircraft density of 200 aircraft per cell, the mean variable guard time would be only around 7.5 % (TSP simulation) of the fixed guard time.

However, it should be noted that even with variable guard times, a theoretical limit for the maximum aircraft density most likely exists. Consider a simplified scenario where each aircraft has to transmit, e.g. one message per second. With fixed guard times, no more aircraft may be in one cell as fixed guard intervals fit into one second. This already assumes message durations approaching zero. Due to power restrictions and limited spectrum resources, this is unrealistic, but the consideration helps to understand the described theoretical limitation. With variable guard times, $E\{D\}/c$ is an indication for the mean guard time needed per aircraft. Notably, $E\{D\}\cdot E\{N\}$ approaches infinity as $E\{N\}$, or ρ, approach infinity for all cases but the one-dimensional case. This suggests that $T_{G,\mathrm{var}}$ approaches infinity as ρ approaches infinity, such that for a certain critical aircraft density, variable guard times would also amount to one second in the example made above. Still, we expect that the limit posed by that is not severe enough to cause a problem to upcoming applications in aeronautics, as is the case for fixed guard times.

4. Message Collisions

Employing the TSP algorithm for an aeronautical network seems to be the perfect solution for the guard time problem. The propagation conditions for a wireless, mobile aeronautical network are in reality expected to be impaired by fading, e.g. caused by banking. The results shown in the previous paragraph are therefore not complete yet. For a more realistic simulation, it has to be taken into account that one aircraft does not receive one message of the other aircraft properly due to a low SNR. Thus, it might calculate a different solution of the TSP and get a different transmission schedule as well. This will induce collisions in the cell and some aircraft might not be able to receive the message properly anymore.

In Figure 11, a map of the collisions is shown. The length of the simulated message was t_M = 280 µs like the length of a UAT message. The color of the map indicates how long the overlap between the messages was and the green cross signifies the wrong transmitting aircraft. The dark red color signifies an overlap over the whole message length of t_M = 280 µs. If two aircraft send a message and a collision occurs, it will typically produce a hyperbolic overlap region. The aircraft that are in this hyperbolic overlap area might not be able to receive both messages correctly. If the aircraft with the wrong schedule sends the message at the same MSO than another aircraft the hyperbolic curve will turn into a straight area and the receive power in the overlap region will be the same for both messages. If, however, the transmit times are not exactly the same, there will be a difference in the receive power and the affected aircraft might receive the stronger message correctly. The color is therefore also an indication of the difference in receiving power of the colliding messages.

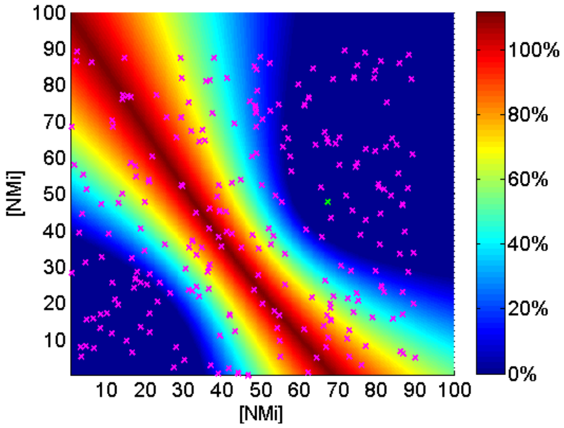

Figure 11: Collision Map For One Aircraft With Wrong Schedule.

In any case, both the aircraft in the overlap region and the other aircraft will notice that a collision of two or more messages has occurred. This circumstance could possibly be used to detect the collisions, since the aircraft that receive both messages correctly (purple crosses on the dark blue surface) know that one aircraft did not keep to its schedule. After all aircraft have sent their messages according to the TSP schedule, one of the aircraft that detected a collision could retransmit the corrupted message of the wrong sending aircraft and thus make it available for the aircraft that are in the red collision area. Or even the aircraft with the wrong schedule could detect that it calculated the schedule wrongly, if it notices a deviation in the transmission order and could withdraw its transmission, so that no collision occurs. It could try to transmit its message after the last aircraft of the frame sent its message, but the end of the schedule would have to be signaled as well. And what happens, if more than one aircraft calculated the wrong schedule? The field of message collision avoidance and detection for the TSP algorithm is an object for further research. Furthermore, the stability of the algorithm, if a collision occurs has to be examined.

5. Conclusion

In this paper, we present a new coordinated access scheme for mobile ad-hoc networks. The nested cell scheme is used to solve the hidden station problem, the near-far problem, and the problem of concurrent transmission and reception on different channels. The nested cells use a combination of FDMA and TDMA for their channels. Within each channel a large number of terminals has to be able to communicate in each frame. With conventional slots with fixed guard times, this would be rather inefficient for short messages given the large cell size. So on top of the nested cell scheme, we propose a TDMA scheme with variable guard times that needs only a small fraction of the fixed guard time. The transmission schedule for variable guard times is calculated with a TSP solving algorithm in a distributed manner on each aircraft. For doing so, the TSP algorithm has to minimize the round trip distance in a set of fully connected nodes. The concept of variable guard times can be used for all types of MANETs, but is particularly beneficial for an aeronautical MANET, because the communication range for an en-route aircraft is very large. Furthermore the difficulties that can occur for a wireless aeronautical network are described in this paper. If collisions of messages take place, there are most probably nodes that detect the collisions. This information could be used to stabilize the TSP algorithm and prevent the increase of collisions due to collisions in the previous step. This topic will be the subject of further research.

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Email Addresses

M. Walter: m.walter@dlr.de

N. Franzen: nico.franzen@dlr.de

M. Schnell: michael.schnell@dlr.de

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