Advanced Aloha with SIC for Beaconing in a MANET

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***Abstract*—Beaconing, the broadcast of information from one user of a network to all others within a certain neighborhood is required for a number of applications. This paper focuses on beaconing in a wireless, infrastructureless network with mobile users. In such a scenario, we analyze the performance of Advanced Aloha, the combination of Aloha with strong protection of messages against interference. Such protection is achieved through coding and other measures. Together with successive interference cancellation, it allows to resolve collisions. Analytical results will be presented for perfect interference cancellation. These include the maximum amount of messages per area and time for which a given communication range may be achieved, as well as the resulting maximum spectral efficiency at a receiver. Signal propagation according to a path loss exponent is taken into account together with a radio horizon limiting node visibility. Notably, this leads to results applicable to freespace propagation in contrast to other work ignoring the radio horizon.**

I. Introduction

Today, many wireless systems have emerged or are under development which serve, exclusively or amongst others, the purpose to let a large number of users periodically broadcast information. One important class are inter-vehicular ad-hoc networks (VANET), a subset of mobile ad-hoc networks (MANET). A VANET typically broadcasts position, intent and other information from each vehicle to all others within vicinity to increase situational awareness. Often, car-to-car communication is associated with the term VANET, together with the IEEE802.11p standard. Another example is COMB, a VANET scheme which has been proposed for broadcast communication between trains [1]. In a broader sense, similar networks with respect to the surveillance functionality exist for ships and aircraft. At sea, the Automatic Identification System (AIS) is used, while the Universal Access Transceiver (UAT) and the Secondary Surveillance Radar Mode S Extended Squitter running on 1090 MHz (1090ES) are two communication systems intended to support the Automatic Dependent Surveillance Broadcast (ADS-B) application on board of aircraft [2].

Another interesting application for broadcasting in a MANET can be found when looking at efficient schemes for multi-hop communication in such a network. The systems described in [3] and [4] both require extensive and up-to-date knowledge at each node of the network about all other nodes within its neighborhood. As long as the neighborhood is small, this may be seen as trivial. Yet, there are scenarios where each node of a network will receive non-negligible signal power from an extremely large number of other nodes distributed over a vast area. One example would be an aeronautical network, where the line-of-sight range between high-flying aircraft is huge. The timely and efficient distribution of complete neighborhood information in such a scenario is a non-trivial broadcast problem.

Motivated by the applications for such a system, this paper investigates the achievable efficiency of MANET beaconing when using advanced Aloha. Herein, advanced Aloha refers to the combination of conventional Aloha with strong protection of messages against interference. Transmitters employ coding, possibly spreading and pseudo-random interleaving, followed by pseudo-random scrambling to achieve the intended protection. In the receiver, successive interference cancellation (SIC) is used to decode colliding messages. An access scheme of this kind has been proposed for satellite communications, at first without SIC under the name of Spread Spectrum Aloha (SSA) in [5] and more recently in [6] with the addition of SIC as Enhanced SSA (E-SSA). It has been shown to be effective for bursty network traffic corresponding to a very high number of users generating relatively small messages, a traffic profile very similar to surveillance beaconing in a MANET. Another description of a similar access scheme for satellite communications may be found in [7], where it is called Spread Scrambled Coded Multiple Access (SSCMA). Furthermore, at least with respect to signal generation some similarities exist between the access schemes considered in this paper and Interleave-Division Multiple Access (IDMA), which is for example described in [8]. Previous work considering the use of spread spectrum methods in a MANET together with multi-user detection (MUD), of which SIC is a special case, can be found in [9]. However, the system considered there uses time slots, which requires time synchronous operation, and control messaging to coordinate channel access. Furthermore, the impact of coding is not analyzed in detail.

The rest of the paper is structured as follows. Section II explains advanced Aloha parameters and constraints in a basic, non-MANET case where all messages are of equal power. Section III details the physical channel loss model used, as well as the network topology model. Then, the main concept necessary for applying the basic results to the MANET case is presented. Section IV outlines the analytical problem solution for perfect successive interference cancellation and presents results. Conclusions are drawn in Section V.

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TABLE I
ADVANCED ALOHA: BASIC NOTATION

Parameter	Definition
L	Information bits per message
a	Information bits per modulated symbol
N	Chips per modulated symbol (spreading factor)
N_s	Length of synchronization sequence in chips
T_c	Chip interval, 1/(Chip rate)
Z	SINR threshold for synchronization
G	No. of messages generated within LT_c
M	Expected number of overlapping messages

II. ADVANCED ALOHA IN A BASIC SCENARIO

At first, advanced Aloha is analyzed for the basic case of all messages having the same power at a receiver and without SIC. Note that for reference, the notation used for advanced Aloha is summarized in TABLE I.

As a general description of message generation in the transmitter, it is assumed that all messages contain L bits of information. Through channel coding and modulation, the information bits are mapped onto a sequence of symbols at a combined rate of a bits per modulated symbol. Each symbol is subsequently spread onto N chips, which can be seen as the additional use of a repetition code [8]. A chip in this context is a Nyquist pulse, and T_c^{-1} is the rate at which the sequence of chips that make up a message is transmitted. Prior to transmission, pseudo-random scrambling and interleaving is applied to decorrelate signal and interference at the receiver. This is similar to IDMA [8]. Furthermore, each message is preceded by a synchronization sequence of N_s chips by which a receiver must be able to detect the message starting instant and the pseudo-random scrambling and interleaving option chosen by the transmitter. A sufficiently high number of such options shall exist in the system, with transmitters choosing one at random for each message, such that the probability of two messages with the same scrambling/interleaving arriving at a receiver with less than one chip offset in time remains small (see also [5]). In the following, it will be assumed that this is the case and the effect of such same-code collisions will be neglected.

On the receiver side, consider the signal to interference and noise ratio (SINR) at the output of a correlator that coherently adds up all N chips belonging to the same modulation symbol for data or all N_s chips of the same synchronization sequence for message detection. N_0 is the one-sided power spectral density of thermal noise at the receiver input. The average received power for one message is denoted by P_rx, such that the energy per chip at the chip matched filter output is $P_\mathrm{rx}T_c$. For interference calculation, it is assumed that M overlapping messages are received at the same time and that all contributions from interfering messages add up incoherently on average. Additionally, this derivation makes the simplifying assumption that messages arrive at a receiver in a chip-synchronous way, i.e. the time difference of arrival between any two messages is a multiple of T_c. This way, the interference caused in one chip by an overlapping message is always equal to the chip energy. Without this simplification, calculating interference contributions would be much more difficult and also depend on the elementary chip waveform used. With theses assumptions and after some calculation, we get the following result for synchronization and data SINR

$$\mathrm{SINR}_\mathrm{sync} = N_\mathrm{s} / \left(M + \frac{N_0}{P_\mathrm{rx}T_c} \right) \ , \qquad (1)$$

$$\mathrm{SINR}_\mathrm{dat} = N / \left(M + \frac{N_0}{P_\mathrm{rx}T_c} \right) \ . \qquad (2)$$

Note that instead of the received power, (1) and (2) may also be expressed in terms of received energy per bit $E_\mathrm{b,rx}$, using the straightforward relationship

$$E_\mathrm{b,rx} = \left(\frac{N}{a} + \frac{N_\mathrm{s}}{L} \right) P_\mathrm{rx}T_c \ . \qquad (3)$$

For the interference, it is now assumed that messages are transmitted by the entirety of transmitters according to a Poission arrival process, in which G messages arrive per LT_c. G may be seen as the offered traffic, normalized to a spectral efficiency of one, or as the input rate in bit per chip at which information flows into the channel. With this assumption, the average M can be found to be

$$M = G \left(\frac{N}{a} + \frac{N_\mathrm{s}}{L} \right) \ . \qquad (4)$$

Substituting (3) and (4) into (1) and (2) yields

$$\mathrm{SINR}_\mathrm{sync} = L / \left[\left(1 + \frac{1}{\xi} \right) \left(G + \frac{N_0}{E_\mathrm{b,rx}} \right) \right], \qquad (5)$$

$$\mathrm{SINR}_\mathrm{dat} = a / \left[(1+\xi) \left(G + \frac{N_0}{E_\mathrm{b,rx}} \right) \right], \qquad (6)$$

with the additional definition

$$\xi := \frac{aN_\mathrm{s}}{NL} \ . \qquad (7)$$

ξ may be seen as the synchronization overhead, as it gives the ratio of chips used for synchronization to chips used for data.

To ensure that all transmitted messages can be correctly received, two fundamental constraints are now formulated. As a receiver does not know a-priori at what points in time messages will start, detecting those points by correlating with the known synchronization sequences of all pseudo-random scrambling and interleaving options is required. In this paper, it is assumed as first constraint (C1) that for this to work, $\mathrm{SINR}_\mathrm{sync}$ has to be above a certain synchronization threshold Z. Secondly, under the simplifying assumption that the sum of all interference resembles Gaussian noise, we use the well-known ergodic capacity result for the amount of bits per channel access that may be successfully transmitted through an additive Gaussian noise channel to get a constraint C2 on the number of bits per modulation symbol a in the interference channel at hand

$$\text{C1:} \qquad \mathrm{SINR}_\mathrm{sync} \geq Z \ , \qquad (8)$$

$$\text{C2:} \qquad a \leq \log_2 \left(1 + \mathrm{SINR}_\mathrm{dat} \right) \ . \qquad (9)$$

The objective in the basic, non-MANET case is now to determine the maximum G for which both (8) and (9) are still fulfilled. A coarse outline of this optimization shall be given. At first, by inserting (5), one may solve (8) for ξ, which results in a modified version of C1

$$\text{C1b:} \qquad \xi \geq \frac{Z\left(G + \frac{N_0}{E_{\mathrm{b,rx}}}\right)}{L - Z\left(G + \frac{N_0}{E_{\mathrm{b,rx}}}\right)} \quad . \tag{10}$$

The next idea is to insert the minimum possible ξ according to C1b into (6) and then into C2, as $\mathrm{SINR}_{\mathrm{dat}}$ will be maximized for minimal ξ. After some more steps, it can be shown that the maximum G will be achieved for $a \to 0$, i.e. for arbitrarily low code rates, and that for this maximum holds

$$G_{\max} = \frac{L}{L\ln(2) + Z} - \frac{N_0}{E_{\mathrm{b,rx}}} \ . \tag{11}$$

Due to the definition of G used here, this result is identical to the maximum spectral efficiency in bits per chip up to which a receiver in such a network can successfully receive all messages. For the more simple case of $Z = 0$, this result can also be found in [10, chapter 15.2].

It is remarkable that the spreading factor N does not explicitly appear in the optimal solution. The solution merely requires that ξ, a simple function of N and other parameters, be chosen such that equality in (10) is given. For small a, which is the choice suggested by the solution, this should typically be possible by setting $N = 1$ and choosing N_{s} accordingly. Revealing in this respect is also that if the ratio N_{s}/N is kept constant, neither $\mathrm{SINR}_{\mathrm{sync}}$ nor $\mathrm{SINR}_{\mathrm{dat}}$ according to (5) and (6) depend on N. This is due to the fact that if one uses more spreading, the increased spreading gain is exactly compensated for by the proportionally increased number of interfering messages. Spreading, however, allows to increase the transmitted energy per bit without increasing the transmit power.

III. Application to the MANET Scenario

Note that the most important notation from this section is summarized in TABLE II for reference.

TABLE II
MANET RELATED NOTATION

Parameter	Definition
α	Channel loss exponent
r_{h}	Distance to the radio horizon
r_{com}	Required communication range
Γ	2-D spatial message density generated within LT_c

A. Physical Transmission Model

In the MANET under consideration, all transmitters transmit with equal power. Still, the received power will not be the same for all messages, but will depend on the distance r between transmitter and receiver. In this paper, the received power is assumed to decrease monotonically with distance according to a channel loss exponent α. Additionally, it is assumed that a radio horizon exists at a distance of r_{h} from a receiver. No power is received from any transmitter beyond the radio horizon. Consequently,

$$P_{\mathrm{rx}}(r) = \begin{cases} P_{\mathrm{rx}}(r_{\mathrm{ref}}) \left(\frac{r_{\mathrm{ref}}}{r}\right)^{\alpha}, & \text{if } r \leq r_{\mathrm{h}}, \\ 0, & \text{if } r > r_{\mathrm{h}}, \end{cases} \tag{12}$$

where $P_{\mathrm{rx}}\ (r_{\mathrm{ref}})$ is the known received power in some reference distance r_{ref}. In the following, results will be presented for $\alpha \geq 2$. $\alpha = 2$ is equivalent to freespace propagation, which may be assumed between aircraft at high altitudes and within line-of-sight. For transmitters close to the ground, propagation similar to $\alpha = 4$ is often called typical in the literature (cf. [11], [12]).

B. Network Topology Model

In this paper, the generation of messages on a two-dimensional plane and in time is modeled by a Poisson point process. Consider once more a time window of LT_c. The spatial message density Γ is then defined as the average number of messages generated per area within this time window. A model of this kind corresponds to a random spatial distribution of network nodes, which is frequently used in the literature for analyzing a MANET, e.g. in [11], [13].

C. Concept of Equivalent Equal-Power Interference

In order to apply the basic equations (cf. Sec. II) to the MANET case, it is helpful to make an intermediate step. Consider a topology of interferers as just described, with the limitation that only nodes within a ring area around a receiver with inner radius r_{a} and outer radius r_{b} are transmitting. Then, suppose that this receiver is trying to decode a message from a distance r. An effective number of messages $G_{\mathrm{eff}}(r, r_{\mathrm{a}}, r_{\mathrm{b}})$, generated on average per LT_c, can then be defined by comparing this situation to an equivalent basic situation. In the latter, all interfering messages are of the same power as the desired message. G_{eff} is the number of messages necessary in the basic situation to cause an average interference power equivalent to that of the actual interference from within the ring area. This leads to the integral

$$\begin{aligned} G_{\mathrm{eff}}(r, r_{\mathrm{a}}, r_{\mathrm{b}}) &= \int_{r_{\mathrm{a}}}^{r_{\mathrm{b}}} \Gamma \left(\frac{r}{r'}\right)^{\alpha} 2\pi r' dr' \\ &= \begin{cases} \frac{2\pi r^2 \Gamma}{\alpha - 2} \left[\left(\frac{r}{r_{\mathrm{a}}}\right)^{\alpha-2} - \left(\frac{r}{r_{\mathrm{b}}}\right)^{\alpha-2}\right], & \text{if } \alpha > 2, \\ 2\pi r^2 \Gamma \ln\left(\frac{r_{\mathrm{b}}}{r_{\mathrm{a}}}\right), & \text{if } \alpha = 2. \end{cases} \end{aligned} \tag{13}$$

It is now straightforward to insert (13) into (4), (5), (6) and (10). Note that P_{rx} and $E_{\mathrm{b,rx}}$ now also depend on r according to (12). Constraints C1 and C2 may now once again be used to determine if for a given set of parameters, the receiver could successfully detect and decode the message.

D. Reception with SIC and Range Requirement

When processing the received signal in a MANET scenario, one obvious way is to start by decoding the strongest message detected and subsequently decode messages in descending order according to their power. As soon as a message has been decoded successfully, it is reasonable to try and subtract it from the received signal. This successive interference cancellation is key to employing advanced Aloha in a MANET, as without it the performance degrades strongly in the presence of unequal signal power [5], [6]. If a receiver following these two basic principles was currently attempting to first detect and then decode a message sent to it from a distance r, then all stronger messages from transmitters closer to the receiver than r would already have been processed, while weaker messages from further away would still be unknown to the receiver. Under the assumption that all of the already processed, inner messages have been suppressed perfectly, it can be analyzed whether the receiver could also successfully detect and decode the current message from distance r. If this is true for all distances $0 < r \leq r_{\mathrm{com}}$, with a maximum required communication radius r_{com}, then the network is currently operating without loss of any relevant messages. What remains is to determine the maximum message density $\Gamma_{\max}$ for which this is possible, and the system parameters coding rate a, spreading factor N and synchronization chips N_{s} for which $\Gamma_{\max}$ is attained.

IV. Perfect Successive Interference Cancellation

A. Analytical Solution

Under the assumption of perfect SIC, no messages from a distance below r interfere with the detection and decoding of a message from a distance r. Hence, only the interference from a ring area centered on the receiver with inner radius r and outer radius r_{h} has to be considered. This may be achieved by using $G_{\mathrm{eff}}(r, r, r_{\mathrm{h}})$ according to (13) in the basic equations and, again, also taking into account that $E_{\mathrm{b,rx}}$ decays with r according to the same law as P_{rx}, given by (12). A way to determine the maximum message density $\Gamma_{\max}$ is shortly outlined in the following and results are presented. At first, one may determine the minimum ξ, for which constraint C1b is not violated for any relevant distance $0 < r \leq r_{\mathrm{com}}$. This can then be used in (6) and C2 to find the maximum Γ for which constraint C2 is fulfilled for all $0 < r \leq r_{\mathrm{com}}$. Perhaps the most important result of this rather lengthy process is that $\Gamma_{\max}$ still is achieved as $a \to 0$, i.e for arbitrarily small coding/modulation rates, and that the remarks on spreading made for the basic case in the last paragraph of Section II are still valid. Looking at the limit for $a \to 0$, there exists a critical radius $r_{\mathrm{crit}}(r_{\mathrm{com}})$, such that correct message detection and decoding is possible as long as

$$G_{\mathrm{eff}}(r_{\mathrm{crit}}, r_{\mathrm{crit}}, r_{\mathrm{h}}) \leq A - B \left(\frac{r_{\mathrm{crit}}}{r_{\mathrm{h}}}\right)^{\alpha} , \qquad (14)$$

where

$$A := \frac{L}{L \ln(2) + Z} , \qquad (15)$$

and

$$B := \frac{N_0}{E_{\mathrm{b,rx}}(r_{\mathrm{h}})} . \qquad (16)$$

Note that for the case of equality, (14) is essentially the same as (11), albeit evaluated at r_{crit}. As long as the maximum required communication radius r_{com} is small, r_{crit} is found to be identical to r_{com}. This is not surprising. However, there exists a threshold radius r_{th} such that

$$r_{\mathrm{crit}} = \begin{cases} r_{\mathrm{com}}, & \text{if } r_{\mathrm{com}} < r_{\mathrm{th}} \ , \\ r_{\mathrm{th}}, & \text{if } r_{\mathrm{com}} \geq r_{\mathrm{th}} \ . \end{cases} \qquad (17)$$

r_{th} is the smaller positive solution of

$$\left(\frac{r_{\mathrm{th}}}{r_{\mathrm{h}}}\right)^{\alpha-2} = \frac{B}{\alpha A}\left(\frac{r_{\mathrm{th}}}{r_{\mathrm{h}}}\right)^{\alpha}(\alpha-2) + \frac{2}{\alpha}, \text{ for } \alpha > 2, \qquad (18)$$

$$\ln\left(\frac{r_{\mathrm{th}}}{r_{\mathrm{h}}}\right) = \frac{B}{2A}\left(\frac{r_{\mathrm{th}}}{r_{\mathrm{h}}}\right)^{2} - \frac{1}{2}, \qquad \text{for } \alpha = 2. \qquad (19)$$

For $\alpha = 2$, (19) can be solved for r_{th} using Lambert's W function. Also, numerical solutions for (18) and (19) are not especially difficult. r_{th} exists because propagation according to (12) is limited by r_{h} and SIC is applied in the receiver. Consequently, the SINR for a message from a distance r will at some point start to grow instead of deteriorate with r.

It is noteworthy that the given solution only exists for sufficiently small N_0. More precisely, if $N_0 > 0$, then a noise radius r_{nx} exists for which the right-hand side of (14) becomes zero. If $r_{\mathrm{nx}} > r_{\mathrm{h}}$, the given solution may be applied directly. Otherwise, no r_{th} exists, $r_{\mathrm{crit}} = r_{\mathrm{com}}$ for $r_{\mathrm{com}} < r_{\mathrm{nx}}$ and communication is not possible beyond r_{nx}.

A special case of the solution is obtained under the Assumption that interference is received from an unlimited area, i.e. $r_{\mathrm{h}} \to \infty$. In this case, $r_{\mathrm{th}} \to \infty$ and hence, $r_{\mathrm{crit}} = r_{\mathrm{com}}$. Then, (13) and (14) for $\alpha > 2$ lead to

$$\pi r_{\mathrm{com}}^2 \Gamma_{\max} = \frac{\alpha-2}{2}\left(A - \frac{N_0}{E_{\mathrm{b,rx}}(r_{\mathrm{com}})}\right) . \qquad (20)$$

$\pi r_{\mathrm{com}}^2 \Gamma_{\max}$ is the maximum possible spectral efficiency in received bit per chip from all transmitters within communication range. It is important to realize that for $\alpha = 2$, the result would be zero. Without a radio horizon, (13) grows to infinity. This means that the interference would not be limited. Hence, for a network in freespace, the radio horizon is an important factor.

B. Results

At first, consider the maximum received spectral efficiency $\pi r_{\mathrm{com}}^2 \Gamma_{\max}$ when a radio horizon does exist. Taking a closer look at the solution, one realizes that $\pi r_{\mathrm{com}}^2 \Gamma_{\max}$ depends only on the ratio $r_{\mathrm{com}}/r_{\mathrm{h}}$ and other parameters. It is therefore possible to provide capacity results for r_{com} relative to r_{h} as displayed in Fig. 1. As parameters, $L = 128$ bits per message and a synchronization threshold of $Z = 10$ dB have been used. Fig. 1 shows results for freespace propagation, i.e. $\alpha = 2$, and for $\alpha = 4$. Also, the noiseless case ($N_0 = 0$) is compared to the situation when the remaining $E_{\mathrm{b,rx}}/N_0$ at the radio horizon is only 5 dB and hence, $B = -5$ dB according to (16). It becomes obvious that even if one tries to communicate to the radio horizon and the $E_{\mathrm{b,rx}}/N_0$ achieved there is only moderate, the achievable spectral efficiency and

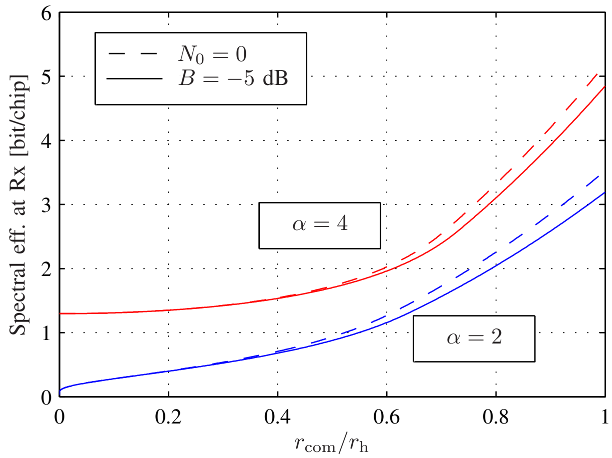

Fig. 1. Received capacity with perfect SIC. $L = 128$ bit, $Z = 10$ dB.

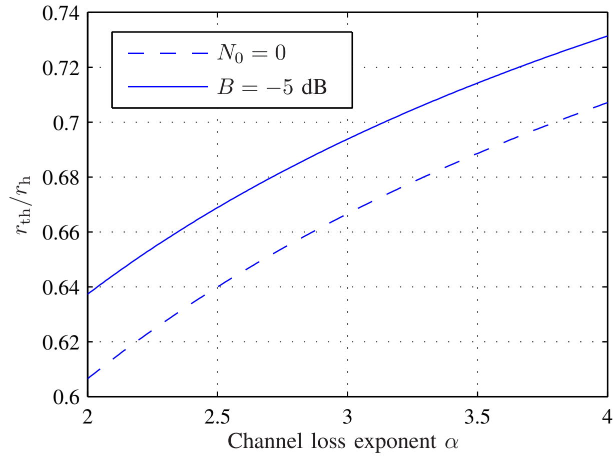

Fig. 2. Threshold radius r_{th} relative to r_h. $L = 128$ bit, $Z = 10$ dB.

also Γ_{max} are not much affected by noise, but largely limited by the multiple access interference. Note that Γ_{max} is a monotonically decreasing function in r_{com} for $r_{com} < r_{th}$, just like one would expect, and stays constant for $r_{com} \geq r_{th}$. The fact that the received spectral efficiency in Fig. 1 increases with r_{com} is due to the fact that for larger r_{com}, the area from which messages are collected grows.

Finally, Fig. 2 plots the relative threshold radius, r_{th}/r_h, versus the channel loss exponent α. Again, the noiseless case and the case of $B = -5$ dB is considered. Note that in the noiseless case, r_{th} is independent of the fundamental system parameters L and Z. For the other case, the same values as before have been used, $L = 128$ bits and $Z = 10$ dB.

V. Conclusion

In this paper, an analytical solution for the achievable message density and received spectral efficiency of advanced Aloha in a broadcast MANET with perfect SIC has been presented. As a key point, the physical propagation model takes into account a radio horizon, which is often omitted in the literature (cf. [11], [13]). This way, results have been derived which are not only valid for a channel loss exponent α sufficiently larger than 2, but include the case of freespace propagation ($\alpha = 2$). Such conditions are for example found in aeronautical scenarios. It becomes clear from the results that freespace propagation is especially challenging for a MANET, as interference received from remote sources is much more severe than in an environment with $\alpha = 4$.

Furthermore, the analysis takes into account the interdependence between coding rate, SINR threshold and interference by looking at ergodic capacity. This leads to an optimization of the coding rate in contrast to other analyses which use a fixed coding rate and SINR threshold (cf. [11], [13]).

The results derived here may be seen as an upper bound on the achievable efficiency, as in reality, interference cancellation will never be perfect. Especially, a node will typically not be able to cancel out its own transmission, i.e. it will not be able to transmit and receive at the same time. How to receive advanced Aloha messages under partial interference cancellation and the capacity achievable under this more realistic assumption will have to be investigated.

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