

Antenna Redundancy for Increasing Transmission Reliability in Wireless Industrial LANs

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Abstract—In this paper we introduce the concept of antenna redundancy, which uses different transmitter antennas for performing retransmissions, however, without transmitting in parallel over multiple antennas and therefore without requiring complex space-time processing techniques in receivers. This allows to keep receivers of small wireless field devices cheap. We investigate for certain wireless channel error scenarios the potential of this approach to transmit data within a prescribed deadline. This question is of utmost importance for wireless industrial communication systems. The results show that antenna redundancy not only reduces the probability of deadline miss exponentially with increasing the number of antennas, furthermore it reduces the expected bandwidth needed to transmit data.

I. INTRODUCTION

The idea to use wireless technology on the factory floor is appealing, and some work has been done to investigate the feasibility and to find sound technical approaches [1], [2], [3], [4], [5], [6], [7], [8], [9], [10], [11]. All approaches are faced to, and some of them seriously consider the problem of supporting hard real-time guarantees despite the “unfriendly” properties of wireless links, which show high error rates and instationary error behavior. Clearly, the goal is to increase the probability of successful and timely delivery of important alarm messages or periodic messages. Some possible approaches are: a) improving the physical layer (e.g. find better modulation schemes, better receivers, increase transmit power, directional antennas, antenna diversity); b) proper frequency and interference planning; c) finding good locations for the wireless stations, and d) improve the lower layer protocols (medium access control (MAC), link layer) with additional mechanisms.

A common approach to improve the lower layer protocols is to use several kinds of redundancy. A well-known example are error-correcting codes (forward error correction, FEC), which add overhead bits to user data in order to correct a number of bit errors [12]. In automatic repeat request (ARQ) protocols a checksum is appended to each packet, which allows to detect almost all errors, but not to correct them. If the receiver detects an erroneous packet, it requests a retransmission [13]. In [3], [4] the idea to use a different spatial channel for retransmitting a packet was introduced (in the context of polling-based MAC protocols). The motivation to do this is to take advantage of the spatial diversity of wireless channels: if station A transmits a packet to the distant stations B and C , then it might well happen that B receives the packet correctly, whereas C

experiences an error. Conversely, if two distant stations A and B transmit a packet to C , C might fail to receive A 's packet but B 's packet is received correctly. This can be explored for retransmissions: if A 's packet fails, B could try its luck with the same packet but over another channel. This kind of “channel hopping” for retransmissions is especially fruitful if the channels exhibit *bursty errors*: if a packet transmitted at time t_0 is received erroneously and the channel is bursty, then the probability that a retransmission at time $t_0 + \tau$ is also erroneous, can reach high values for small to moderate values of τ . Error bursts on wireless channels often last some tens of milliseconds, which covers multiple packets and renders immediate retransmissions useless.

This paper introduces and evaluates a generalization of the idea to use different spatial channels. This approach is called *antenna redundancy*. The idea is to equip a central station (base station, access point) with a number K of spatially separated antennas, and to switch the antennas in a round-robin fashion when performing retransmissions for frames directed from the base station to a wireless station. As an example, the first packet is transmitted on antenna 1, the first retransmission on antenna 2, the second retransmission on antenna 3 and so forth. Alternatively, a number K of tightly synchronized and coupled base stations can be used to achieve the same effect. Theoretically, one could also use different center frequencies to obtain different channels, but using multiple antennas and spatially diverse channels is more advantageous if obstacles move from time to time in the path between transmitter and receiver, which might happen due to mobility.

We investigate for important messages transmitted from the base station to a wireless station the fraction of these missing a prespecified deadline, given that the channel has a certain form of bursty error characteristics, as they are typical for wireless channels. We show by simulations that antenna redundancy significantly decreases the probability of deadline miss for bursty channels. The gain can be as much as an order of magnitude per additional antenna. In addition, antenna redundancy can save a significant amount of bandwidth. Further bandwidth can be saved by using another optimization, the *antenna reuse policy*: the first trial of a new message uses the antenna over which the last successful packet was transmitted, instead of always starting with the same antenna.

The paper is structured as follows: in the next Section II we explain in greater detail the system model and the antenna

redundancy approach. Following this, in Section III we discuss the most important characteristics of wireless channels. The simulation setup is outlined in Section IV and the simulation results are presented in Section V. Our conclusions are given in Section VI.

II. APPROACH AND SYSTEM MODEL

We consider a system consisting of one central station, which has K spatially distributed antennas, numbered from 1 to K .¹ The mutual distance between the antennas is assumed to be much larger than the wavelength used by the wireless transmission system (see below). There is one single mobile station and a separate wireless channel between the mobile station and each antenna (see Figure 1); the channel between antenna i and the mobile is denoted as C_i . The notion of a wireless channel used here encompasses the transmitter modem, the propagation environment between transmitter and receiver (number of air paths, their respective attenuation, interferers, and so forth), and the receiver modem. The most interesting property of a wireless channel for our purposes is how it influences the transmitted bit patterns, i.e. its error behavior on the bit level.

In this paper we assume that the channels C_1, \dots, C_K are stochastically independent. This corresponds to the case where the generation of errors is dominated by multipath fading. Beyond a geographical distance of half a wavelength between the antennas the channels are often found to be uncorrelated [14, Chap.7]. Because of its theoretical utility, however, we make this assumption a little bit stronger and assume the channels to be independent (and hence uncorrelated). If the error behavior would be dominated by interference (e.g. the wireless station is located close to a microwave oven), then different channels would probably show strongly correlated error behavior.

In the antenna redundancy approach with K antennas a packet directed from the central station to the mobile station is first transmitted over antenna 1. If there is need for a retransmission, then antenna 2 is used. If another retransmission is needed, antenna 3 is used and so forth, until the packet is successfully received or a prescribed deadline for transmitting the request expires. The antennas are used in round-robin fashion. If all channels are independent, the transmissions can be seen as a series of independent Bernoulli trials. In the other direction, if the mobile station wants to transmit a packet to the central station, it suffices if at least one of the antennas captures the packet successfully. This assumes that the central station is equipped for receiving K copies of the same packet

¹Instead of having one central station with K antennas we could also assume to have K tightly coupled and spatially distributed central stations. To implement the protocol envisioned in this paper they have to be connected by a fast and (nearly) error-free backbone independent of the wireless channel, and they have to cooperate closely. In the remaining paper, when speaking about the K antenna approach, the approach of having K central stations is also included. Furthermore, it should be noted that there is no technical reason to restrict the antenna redundancy approach to the base station. However, this scenario fits very well the master/slave communication relationship of many industrial communication systems, e.g. PROFIBUS-DP.

in parallel. Furthermore, in the case that all K antennas deliver an erroneous copy of the packet, the central station might try to figure out the correct packet by performing a bit-by-bit majority voting procedure [15, Chapter 4]. However, we do not consider the resulting reliability gain in this paper.

In fact, antenna redundancy is a kind of diversity scheme [14, Chapter 7]. For the case of the mobile host sending a packet to the central station (uplink), the multiple antennas provide *receiver diversity* (space diversity [16]). For the downlink case the antenna redundancy approach has some similarity to transmitter diversity, but there are important differences. Transmitter diversity is mainly applied in *MIMO systems* (Multiple Input, Multiple Output) to increase the channel capacity. At the transmitter side the user data stream is demultiplexed into n_T substreams, where n_T is the number of transmit antennas. Each substream is channel-coded and the substreams are transmitted in parallel. The receiver has to recover the substreams and to combine them into a user data stream. A contemporary implementation of a MIMO system is the Bell Labs BLAST scheme [17]. However, multiple transmitter systems require a significant amount of signal processing at the receiver, which in turn increases complexity and cost of receivers. For the time being, they seem not to be a good solution for wireless coupling of small field devices like sensors to a central station. In the antenna redundancy scheme only a single antenna is used at a time, which allows to keep the receivers of field devices simple.

In this paper we consider the following communication scenario: we denote as a *request* a piece of data which has to be transmitted within a prescribed deadline from the central station to the mobile station. This piece of data is encapsulated into a *packet*, which is transmitted as often as needed to reach the mobile station or to miss its deadline. Each packet is equipped with a perfect checksum, i.e. we deliberately exclude those rare cases where an erroneous packet is accepted as a correct one. When the receiver receives the packet correctly, it sends an acknowledgement frame. We assume the ack to be transmitted in zero time and error-free. After the deadline has passed without getting an ack, the transmitter discards the request and marks it as *failure*. In the other case the request (or one of the corresponding packets) was successfully received by the mobile station and we have a *success*. By these definitions, a request leads to one or more identical packets transmitted from the central station to the mobile station until proper reception or deadline miss.

III. ERROR BEHAVIOR OF WIRELESS CHANNELS

It is commonplace that transmission over wireless channels is much more error-prone than using cable-based media. The error patterns that lower layer protocols (MAC, link layer protocols) are exposed to, are influenced by multiple factors, some of them are: frequency, modulation scheme, interference patterns, propagation environment (number of paths and their attenuation), mobility and the imperfections of transmitter and receiver circuitry. With respect to creating a wireless industrial

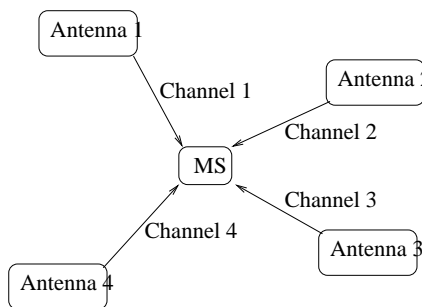


Fig. 1. Example Scenario with four Antennas and a single Mobile Station (MS)

LAN the nowadays popular, mature, standardized and constantly evolving IEEE 802.11 wireless LAN technology [18] is an attractive choice. Some measurement studies investigate the error behavior of IEEE 802.11 radio modems in industrial environments (e.g. [5], [19]). These measurements showed some characteristics which we take as basis and motivation for this work:

- Time-varying behavior over several timescales
- Large variability in the distributions of the lengths of error bursts and error-free periods (some measurements even tend to show heavy-tailed distributions [20]).
- Bursty errors / long-lasting correlation.
- Sometimes comparably high bit error rates up to $10^{-3} \dots 10^{-2}$.

A. Stochastic Models for Generating Bit Errors

Stochastic models of communications channels are often used for simulation-based performance evaluation of communication protocols. Different types of models are used for different evaluation purposes, e.g. packet-level models are often used for evaluation of link layer and higher layer protocols, bit-level models for assessing coding schemes, while other models emphasize propagation aspects and are used, e.g., for evaluating modulation schemes.

For the packet- and bit-level models often simple stochastic processes (e.g., Markov chains) are used, which in turn use a set of parameters. Roughly speaking, there is a trade-off between the model complexity (measured as number of parameters) and the models accuracy in matching certain error statistics, as they are desired by the model's user or found in error traces. There are a lot of stochastic channel models, however, in this paper we focus on two of them: the *Gilbert-Elliot model* uses a two-state time-homogeneous discrete time Markov chain to describe the channel variations. This definition implies geometrically distributed state holding times, which, however, is often not very accurate. The *Semi-Markov model* is a variation of the Gilbert-Elliot model with state holding times that are not geometrically distributed, but have a quantized lognormal distribution, where mean value and variance of the distributions can be prescribed arbitrarily.

The Gilbert-Elliot model is a popular model for wireless bit errors, since it is complex enough to capture burstiness and simple enough to be treated analytically.

B. The Discrete-Time Gilbert-Elliot Channel Model

The Gilbert-Elliot model is a two-state time-homogeneous discrete time Markov chain (TH-DTMC) [21], [22]. The model works with slotted time, the state transitions happen at times $(X_n)_{n \in \mathbb{N}_0}$. The time between X_n and X_{n+1} is considered to correspond to one bit duration. The state space of the TH-DTMC contains only the two states *good* ($=0$) and *bad* ($=1$).

The state of slot X_{n+1} is determined at its beginning according to a Bernoulli experiment: if $X_n = 0$ then $X_{n+1} = 0$ with probability $p_{g,g}$ and $X_{n+1} = 1$ with probability $1 - p_{g,g}$. Accordingly, if $X_n = 1$ then $X_{n+1} = 1$ with probability $p_{b,b}$ and $X_{n+1} = 0$ with probability $1 - p_{b,b}$.

The state holding times are geometrically distributed, the mean state holding times for the good state $E[H_0]$ and the mean state holding time for the bad state $E[H_1]$ are given by:

$$E[H_0] = \frac{1}{1 - p_{g,g}} \quad (1)$$

$$E[H_1] = \frac{1}{1 - p_{b,b}} \quad (2)$$

During the bad channel states each transmitted bit is subjected to an independent Bernoulli experiment to determine whether it is transmitted erroneously or correct. Let p be the bit error probability. During the good state no bit errors occur.

IV. SIMULATION SETUP

We have implemented a simulation model of the system described in Section II using a commercial simulation library. The simulation model was validated by code inspection, by careful analysis of generated event sequences and by comparison of the simulation results with results obtained from an analytical model for the case of a Gilbert-Elliot channel. The analytical model will be discussed in a subsequent publication.

A. Performance Measures

There are different interesting performance measures for a request:

- Given a deadline d seconds (or equivalently: the bound of D trials for a packet of length l bits), what is the probability that the request will miss its deadline due to no packet reaching the receiver? We denote this as *failure probability*.

- Given no deadline, we can ask for the 99% percentile of the time needed to successfully (i.e. acknowledged) transmit a request to the mobile station. This quantity is introduced in [4] and denoted as *confirmation delay* \overline{D}_C .

However, in this paper we restrict to the failure probability. All simulations were carried out such that a minimum of 10 million requests and a maximum of 100 million requests was transmitted. If in between these bounds the confidence interval for the failure probability is with 95% confidence smaller than 2% of the mean value then the simulation is stopped. This high number of requests is needed to obtain statistically significant results for small failure probabilities.

B. Parameters

The simulator allows to vary the following parameters:

- K is the number of base station antennas (or tightly coupled base stations).
- l is the length of a packet.
- D is the number of admissible trials before a packet of length l misses its deadline.
- p is the bit error probability during the bad state of the Gilbert-Elliot channel.
- $p_{g,g}$, and $p_{b,b}$ describe the state transition probabilities of the Gilbert-Elliot channel and thus their (mean) state holding times and the steady state probabilities to find the system in either state.
- b is the bit rate.
- ω is the interarrival time of requests at the base station. The requests are assumed to arrive periodically.

It is appropriate to fix some parameters in advance. The bit rate b is 1 Mbit/s. On each channel C_i runs a separate instance of a channel error model (Gilbert-Elliot or Semi-Markov). For all channels the mean bad burst length is set to 10 ms (corresponding to 10.000 bits), and the mean good burst length to 65 ms (corresponding to 65.000 bits). The bit error probability p during the bad state is set to $p = 1$. These mean burst lengths are similar to those used in [23], which in turn were derived using a methodology described in [24], where the parameters of a N -state Markovian channel model are derived from some simple physical parameters like wavelength, Doppler frequency etc. These numbers lead to a rather bad channel: the steady-state probability for finding the channel in bad state is approximately 13.3%. For the Semi-Markov model we have chosen the mean good and bad burst lengths the same as for the Gilbert-Elliot model. However, inspired by the results of the measurement study [19] we set the coefficient of variation for the bad state holding times to 10, and for the good state to 20. This means that the channel state holding times are much more variable, with longer holding times occurring with higher probability than for the Gilbert-Elliot model.

The packet length l was set to 416 bits, corresponding to the 192 μ s PHY header of an IEEE 802.11 compliant radio modem with DSSS PHY, plus eight bytes MAC header, plus 20 bytes user data and checksum. PHY header bits, MAC

header bits and user data bits are treated in the same way.² The deadline was set to a maximum of $D = 10$ trials, higher numbers need unacceptable simulation runtimes to achieve a certain accuracy. The other parameters were varied according to the needs of different experiments.

V. SIMULATION RESULTS

We present the results for two different simulation experiments. The first experiment investigates the effectiveness of the antenna redundancy approach, and the second experiment investigates a further optimization, the so-called *antenna-reuse policy*.

A. Experiment: Effectiveness of Antenna Redundancy

In this experiment we investigate the influence of antenna redundancy on the failure probability for the two different channel models, the Gilbert-Elliot model and the Semi-Markov model. The experiment is designed such that the requests have a large interarrival time (100 seconds), which means that they hit the respective channels in steady-state conditions. The fixed and variable parameters of this experiment are summarized in Table I. Please note that we vary only the parameter K .

In Figure 2 we show the failure probability vs. the number of antennas K , and in Figure 3 we present the mean number of trials needed to handle a request. The following points are remarkable:

- Each additional antenna buys approximately one order of magnitude lower failure probability, the decrease is exponential in K . With six antennas it is below 10^{-5} for both types of channels.
- The failure probability results for the Semi-Markov channel are almost consistently worse than for the Gilbert-Elliot channel, for $K = 6$ the low number of events may bias the results. An explanation for this is discussed in Section V-B.
- For both channels the mean number of trials reduces significantly when adding a second antenna, the third and all further antennas have almost the same performance. Therefore, already with the second antenna not only a reduced failure probability but also a reduced bandwidth need can be reached. The reduction for increasing K can be explained by the fact that it takes longer before the base station is forced to return to an antenna which already experienced a transmission error.

B. Experiment: Effectiveness of the Antenna-Reuse Policy

In this section we describe some simulation results for the non-steady-state case: in this case the interarrival times between requests are small and the channel could not be expected to have reached the steady-state. Instead, it can be expected to be correlated from request to request. The arrival times chosen in this experiment are of practical interest

²This assumption is inaccurate with respect to the PHY header, which main purpose is to allow the receiver to acquire bit synchronisation. Hence, it is not appropriate to talk about bit errors here, since the receiver has no access to single bits during the PHY header.

Parameter	Value
K	1, 2, 3, 4, 5, 6
l	416 bits
D	10
interarrival time	100 s
error models	Gilbert-Elliot ($p = 1$), Semi-Markov ($p = 1$)

TABLE I
PARAMETERS FOR EXPERIMENT “ANTENNA REDUNDANCY FOR DIFFERENT CHANNELS”

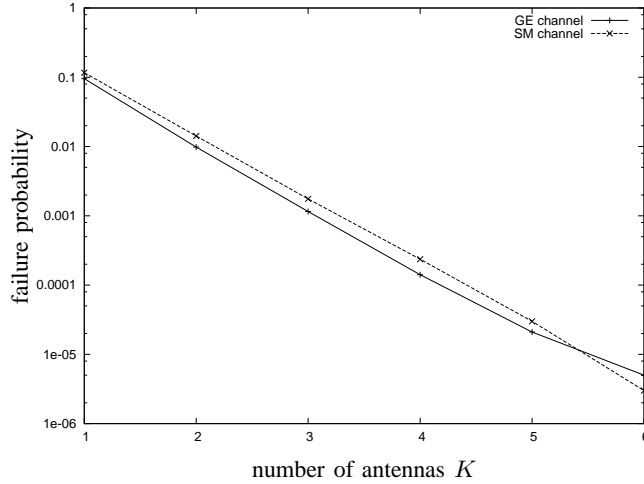


Fig. 2. Failure Probabilities for the experiment “effectiveness of antenna redundancy” for two different channel types

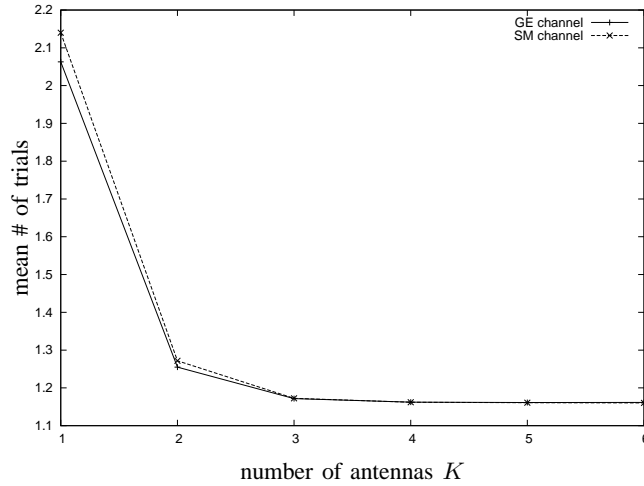


Fig. 3. Mean number of trials for the experiment “effectiveness of antenna redundancy” for two different channel types

for industrial applications: they are in the range of 5 to 30 milliseconds.

We are not only interested in evaluating the failure probability for this case, but we also want to evaluate the *antenna reuse strategy*: in the strategy described in Section II the base station starts each new request with antenna 1, while in the antenna reuse strategy it starts with the antenna where the last successful packet was transmitted. The effects of this strategy are evaluated for the two different channel error models.

The fixed and variable parameters of this experiment are

summarized in Table II.

In Figure 4 we show the failure probability for the two channel types and the two antenna reuse strategies. The following points are remarkable:

- For both the Gilbert-Elliot model and the Semi-Markov model the failure probabilities are not sensitive against the arrival period, the “steady-state” interarrival period of 100 seconds shows almost identical results as for the much smaller arrival periods.
- The Semi-Markov model has significantly higher failure

Parameter	Value
K	3
l	416 bits
D	10
interarrival time	5, 6, 7, 8, 9, 10, 12, 15, 20, 30, 40, 50 ms
error models	Gilbert-Elliot ($p = 1$), Semi-Markov ($p = 1$)
antenna reuse	yes, no

TABLE II
PARAMETERS FOR EXPERIMENT "EFFECTIVENESS OF THE ANTENNA REUSE POLICY"

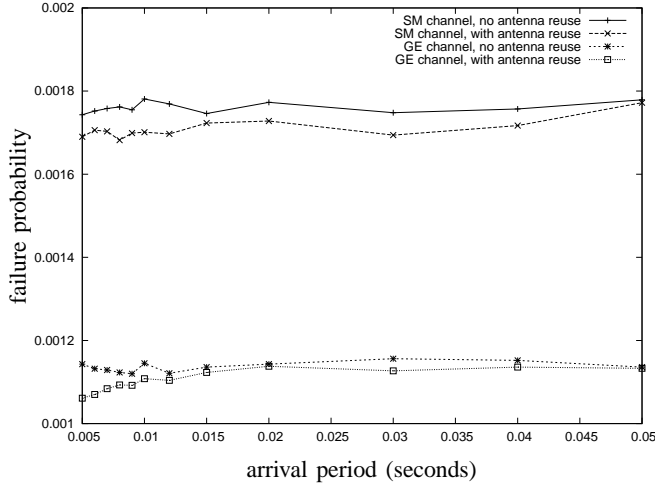


Fig. 4. Failure Probabilities for the experiment "effectiveness of antenna reuse policy" for two different channel types

	Gilbert-Elliot	Semi-Markov
# of failure bursts	17618	11552
mean failure burst length	1.2968554 requests	3.0114267 requests
product (= number of failures)	22848	34788

TABLE III

COMPARISON OF FAILURE BURST STATISTICS FOR $l = 416$, $t = 0$, $R = 1$, $D = 10$, $K = 3$, 5 MILLISECONDS ARRIVAL PERIOD, WITHOUT ANTENNA REUSE AND 20 MILLION REQUESTS

probabilities than the Gilbert-Elliot model (increased by more than 50%), hence, the increased variability reduces the system reliability. This can be explained as follows. The lognormal distributions used for the channel state holding times have comparably large coefficients of variation. The first packet of a request transmitted on one of the $K = 3$ channels corresponds to a random sampling during either a good or a bad channel state holding time. From renewal theory [25] we know that in the steady state for an arbitrary interarrival time distribution X the expected value of the residual lifetime (i.e. the expected time the system stays in the same state before switching) is given by:

$$\frac{E[X^2]}{2E[X]} \quad (3)$$

which we can rewrite using the squared coefficient of

variation $C_X^2 = \frac{\text{Var}[X]}{(E[X])^2}$ as:

$$E[X] \cdot \frac{1 + C_X^2}{2} \quad (4)$$

The geometric distributions used in the Gilbert-Elliot model have a coefficient of variation smaller than one, while for the Semi-Markov model we have used much higher values. Therefore, the above formula gives much higher expected residual lifetimes for the Semi-Markov model. This has the consequence that once a channel is found in the bad state, it will likely stay in this state for longer time than in the Gilbert-Elliot model. The same holds true for the good state holding times. To illustrate this, we denote successively failed requests as a *failure burst*. We compare in Table III for a specific example the statistics of failure bursts for both the Gilbert-Elliot model and the Semi-Markov model, both taken for the same parameters and 20 million requests. It can be seen that the increased length of the failure bursts for the Semi-

Markov channel outweighs their more rare occurrence, which in turn explains the higher failure probability for the Semi-Markov model.

- For the Semi-Markov model the difference between the strategies with and without antenna reuse is statistically significant. It can be seen that the antenna reuse policy gives a small reduction in the failure probability, while for the Gilbert-Elliott model the differences tend to be negligible for arrival periods larger than 10 milliseconds.

In Figure 5 we show the mean number of packets needed to handle a request (clearly, these numbers are proportional to the mean confirmation delay a request experiences, i.e. the time between arrival of the request and the time instant where its fate is known). Two conclusions can be drawn:

- For both channel error models the strategy without antenna reuse delivers almost the same performance, and in both cases the antenna reuse scheme reduces the number of packets needed to handle a request, which is equivalent to a bandwidth reduction. However, in both cases the mean number of packets increases for increasing arrival period, until eventually the antenna reuse strategy gives no gain over the case of no antenna reuse.
- The larger variability of the channel state holding times for the Semi-Markov model makes the antenna reuse strategy much more effective than for the Gilbert-Elliott model. As stated above, once the channel is in the good state (as is the case for the last packet of the preceding request) it can be expected to stay here for much longer time as for the Gilbert-Elliott channel. Hence, the next packet on this channel (aka: the first packet of the next request) is more likely to succeed and to reduce the number of packets to one.

To summarize, for small request interarrival times and channels with some memory (like the Gilbert-Elliott and Semi-Markov channels) the antenna reuse strategy reduces the failure probabilities only by a small amount, but it reduces the number of packets needed to transmit a request significantly, which saves bandwidth and power.

VI. CONCLUSIONS

The antenna redundancy approach explores the advantages of transmit diversity (and of receiver diversity in the case of packets sent from the wireless station to the access point) while keeping the complexity of the receiver low, as compared to true transmit diversity/MIMO systems. This makes antenna redundancy attractive for scenarios where the wireless stations are small and cheap field devices.

For the case of independent (and rather bad) channels between the antennas and a wireless station the antenna redundancy approach decreases the failure probability (i.e. the probability of a request to miss its deadline) exponentially in the number of antennas. For the investigated scenario the difference is approximately one order of magnitude per additional antenna. In addition, already for the second antenna we achieve a significant reduction in the mean number of

packets needed to transmit a request. This saves an enormous amount of bandwidth, which can be used to serve other wireless stations. When additionally the antenna reuse strategy is used, then for scenarios with low request interarrival periods (as often found in industrial applications) further bandwidth savings can be achieved.

In our further research we will investigate the effectiveness of antenna redundancy for cases where the channels are not independent but correlated, e.g. for the case where the wireless station is located close to an interferer.

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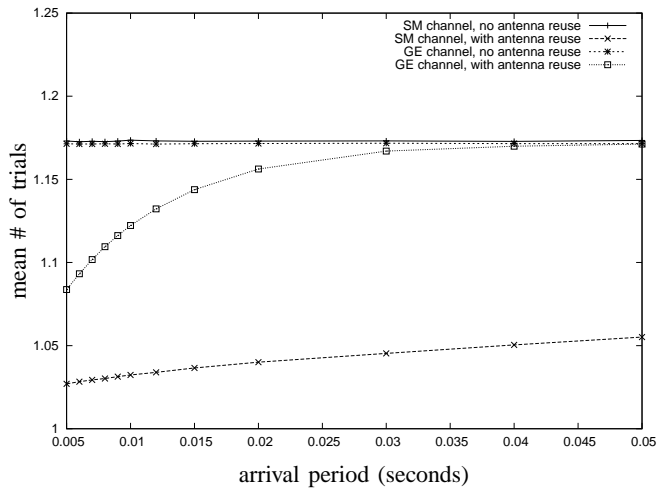


Fig. 5. Mean number of trials for the experiment “effectiveness of antenna reuse policy” for two different channel types

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