Delay Analysis of Group Handover for Real-Time Control over Mobile Networks

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***Abstract*—Future mobile networks will provide support for real-time control applications. The tight real-time and reliability constraints of these applications introduce novel challenges for mobility management. Legacy individual handover schemes do not sufficiently address these issues, as they do not consider physical interactions between mobile nodes. A novel group handover scheme is proposed which allows for the simultaneous handover of a group of nodes. Both the individual and the group handover are modeled as discrete-time Markov chains. Based on these models expressions for the stochastic handover delay are derived. The results are numerically evaluated in a vehicle platooning scenario. The group handover is shown to significantly reduce the handover delay in comparison to the individual handover. Furthermore, the group handover is shown to scale well when the number of vehicles increases. These improvements are shown to come at the cost of an increased messaging overhead.**

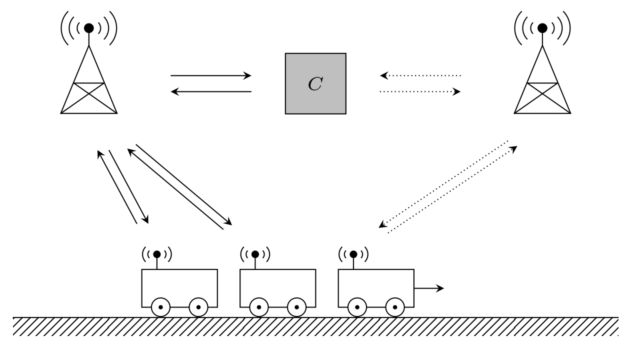

Figure 1. The vehicles in the platoon are controlled by a centralized controller C. During the handover all vehicles need to be handed over from the source base station on the left to the target base station on the right.

I. Introduction

Handover is an essential feature of large-scale mobile communication systems. It has been subject to a long evolution, originally being employed only for voice communications. With the arrival of packet-switched mobile networks, handover needed to be harmonized with the requirements of mobile IP. More recently, handover has been considered for larger groups of mobile nodes, for instance, in the context of trains and buses. In these scenarios the communication streams that need to be considered originate from legacy IP-based applications, such as web browsing and video streaming. In recent years, however, more research attention is focusing on machine-type applications. Of particular interest are critical machine-to-machine applications, which generally arise in cyber-physical systems. In these systems a set of plants is envisioned to be controlled over the mobile network. This leads to various novel requirements, sparking the large research interest in ultra-reliable low-latency communications. One of the major challenges is to achieve extremely low end-to-end latencies, while at the same time decreasing the packet error rates by several orders of magnitude. These requirements introduce novel challenges for mobility management. Of particular importance is the issue of handing over a group of physically interconnected plants.

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For illustration purposes a vehicle platooning scenario is considered, as shown in Figure 1. The platoon is controlled by a centralized controller C, which regulates the distances between the vehicles. The control algorithm is envisioned to run somewhere in the mobile network, realized by either cloud or edge resources. In such a scenario, the vehicles are initially connected to the source base station (BS). When moving out of the communication range of the source BS, the vehicles need to be handed over to the target BS. As the control of the vehicle platoon comes with tight real-time and reliability constraints, it is clear that handing over the radio links comes with novel challenges. The handover might introduce additional packet losses and delays, which can affect the stability and performance of the control system. Furthermore, during the handover the control system might be temporarily in open loop. This raises the question whether this impact on the control system can be minimized or avoided.

These issues have not been sufficiently addressed in related work so far. The general idea of moving control algorithms to the cloud has been investigated in [1] and [2]. A vehicular scenario is considered where part of the control functionality is implemented in the cloud. The impact of the delay introduced by the cloud on the control performance is investigated. However, the implications of possible handovers are not considered. From a communications perspective, the performance of current handover schemes has been extensively studied [3] [4] [5]. Most of these investigations, however, have been done either through simulations or experiments, without providing a systematic

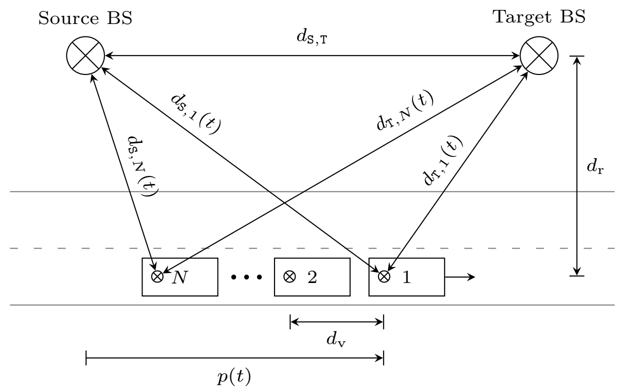

Figure 2. Geometric view of the considered platooning scenario.

framework for systems design. To the best of the authors' knowledge, the consequences of handing over multiple nodes have not yet been investigated. Group handover schemes have so far mainly been studied in the context of high-speed trains [6] [7]. A scenario is considered where the users are communicating over a relay station. Thus, the individual users can be handed over by handing over the relay station. Clearly, for the platooning scenario this scheme cannot be applied.

This paper provides two key contributions to the open problem of handover in critical machine-type applications. First, an analysis of legacy individual handover schemes is presented in terms of their stochastic handover delay. Under reasonable system assumptions it is shown that individual handover schemes do not sufficiently address the anticipated requirements of real-time control applications. In these schemes the vehicles of the platoon undergo the handover procedure individually. This significantly increases the time span between all vehicles being associated with the source BS and all vehicles being handed over to the target BS. Second, a novel group handover scheme is proposed and analyzed. This handover scheme is shown to drastically reduce the handover delay by simultaneously handing over all vehicles.

The remainder of this paper is organized as follows. Section II defines the considered problem. Sections III and IV describe the modeling of the individual and group handover schemes, respectively. Section V analyzes the performance of these schemes in terms of the handover delay. The results are numerically evaluated in Section VI. Last, conclusions and suggestions for future work are presented in Section VII.

II. System Model and Problem Formulation

Consider the setup shown in Figure 1 consisting of a group of mobile nodes. These nodes are jointly controlled over the mobile network, which consists of a source BS $\mathtt{S}$ and a target BS $\mathtt{T}$. Each node sends its sensor measurements to a centralized controller C, which in turn computes the control inputs for all nodes. Each node typically contains a low-level control system that processes the received control inputs. In this paper a platooning scenario is considered, which is shown in Figure 2. The vehicle platoon consists of N vehicles, where the set of vehicles is denoted by $\mathcal{V} = \{1, \ldots, N\}$. Let the longitudinal position of the lead vehicle at time t be denoted by $p(t)$. The distance between the vehicles is given by d_{v}, and the distance between the BSs and the road is given by d_{r}. Furthermore, the distance between entities x and y is denoted by $d_{x,y}$. All vehicles periodically communicate their position, velocity, and radar measurements to the centralized controller. The centralized controller in turn sends back control commands to regulate the distances between the vehicles. Initially, all vehicles are connected to the source BS. While driving, the vehicles move out of the range of the source BS, so they need to be handed over to the target BS. In the remainder of this section the communication system model and handover model are described in detail, after which the problem statement is presented.

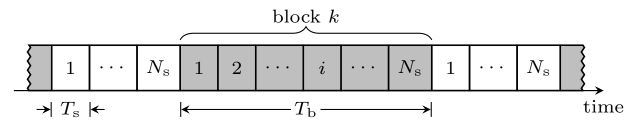

Figure 3. Time division frame structure with N_{s} slots per block.

A. Communication System Model

The vehicles communicate with the centralized controller over the mobile network. For each vehicle and BS pair, time is assumed to be divided into slots of length T_{s}. The communication in each slot is governed by the associated BS. The slots are used to communicate handover messages, while the measurement and control packets are not modeled. A single antenna system is used, which has a bandwidth denoted by W. Furthermore, the transmit power is assumed to be fixed and given by P_{tx}. The BSs are assumed to operate on different frequency bands, so the inter-cell interference can be neglected.

In modeling the channel between vehicle $v \in \mathcal{V}$ and BS $b \in \{\mathtt{S}, \mathtt{T}\}$ the effects of path loss, shadowing, and fading are considered [8] [9]. In order to model the shadowing and path loss effects of the wireless channel the slots are further grouped into blocks. Each block contains N_{s} slots, as shown in Figure 3. During each block of duration T_{b} the path loss and shadowing are assumed to be constant. The path loss in block k is given by $h^2_{\mathrm{PL},b,v,k} = \kappa_0 d^{-\eta}_{b,v,k}$, where κ_0 is the path loss gain at reference distance d_0, η is the path loss exponent, and $d_{b,v,k}$ is the distance between BS b and vehicle v. The shadowing is log-normally distributed and given by $h^2_{\mathrm{SH},k} = e^{\lambda_k}$ with $\lambda_k \sim \mathcal{N}(0, \sigma^2_\lambda)$, where σ_λ is the standard deviation. The standard deviation in dB is denoted by $\sigma_{\lambda,\mathrm{dB}}$, which is related to σ_λ by $\sigma_\lambda = 0.1 \ln(10) \sigma_{\lambda,\mathrm{dB}}$ [9]. The shadowing is assumed to be independent and identically distributed between blocks. During each slot i the fading is assumed to be constant, and is modeled by a Rayleigh distributed process with unit mean. The fading is given by $h^2_{\mathrm{FA},k,i}$, which is assumed to be independent and identically distributed between slots and blocks. The path loss model and the statistics of the shadowing and fading distributions are assumed to be known both at the transmitter and the receiver. Let the random average signal-to-noise ratio (SNR) in block k for BS b and vehicle v be defined as

$$\bar{\gamma}_{b,v,k} = \frac{h^2_{\mathrm{PL},b,v,k} h^2_{\mathrm{SH},k} P_{\mathrm{tx}}}{\sigma_n^2}, \quad (1)$$

where σ_n^2 is the noise power. The instantaneous SNR can then be written as $\gamma_{b,v,k,i} = \bar{\gamma}_{b,v,k} h^2_{\mathrm{FA},k,i}$. Furthermore, the received signal strength (RSS) metric is considered, which is defined as

$$R_{b,v,k} = P_{\mathrm{tx}} + 10 \log_{10}(\kappa_0 d^{-\eta}_{b,v,k}) + \lambda_{k,\mathrm{dB}}, \quad (2)$$

where $\lambda_{k,\mathrm{dB}} \sim \mathcal{N}(0, \sigma^2_{\lambda,\mathrm{dB}})$.

Depending on the SNR in each slot, a varying amount of bits can be successfully transmitted over the wireless channel. The maximum capacity of the wireless channel for BS b and vehicle v in block k and slot i is assumed to be given by

$$c_{b,v,k,i} = W \log_2 (1 + \gamma_{b,v,k,i}). \quad (3)$$

A packet transmission of $\rho_{v,k,i}$ bits requires a rate of at least $r_{v,k,i} = \rho_{v,k,i}/T_{\mathrm{s}}$ bits/s. The packet is successfully decoded at the receiver if the instantaneous SNR $\gamma_{b,v,k,i}$ is greater or equal to the SNR threshold $2^{r_{v,k,i}/W} - 1$, otherwise the packet is considered to be lost. A lost packet is detected at the transmitter by a missing acknowledgment.

B. Handover Model

The handover schemes are modeled by the handover message flow and the triggering rule. During each block the vehicles measure the channels of the nearby BSs and report the measurements to the source BS. Based on these measurements and the triggering rule, the source BS makes a handover decision for the next block. If a handover is triggered, the handover message flow is executed at the start of the next block. The duration of the message flow is given by T_0, which is assumed to be smaller than the duration of a block T_{b}. The message flow is divided into a preparation, an execution, and a completion phase, and is modeled by the sequence $\mathcal{M}$. This sequence includes only the messages over the radio interface, while the messages over the backbone are assumed to be error free. Every message in $m \in \mathcal{M}$ has an associated packet size ρ_m. Each message is further assumed to be transmitted in one time slot, so the transmission rate for each message is given by $r_m = \rho_m/T_s$. Each message is acknowledged by an acknowledgment message, which is assumed to be error free. A failed message is indicated by the lack of an acknowledgment, and is retransmitted a maximum of N_{ret} times.

C. Problem Statement

While the platoon is moving between BSs it can be disturbed by the execution of handovers in two ways. First, measurement and control packets may experience varying delays and packet error rates while vehicles are connected to different BSs. Second, during the execution of a handover vehicles may be disconnected for a certain duration. In order to minimize the impact of these disturbances the handover delay must be kept small. Let the handover delay be defined as the time between the handover being triggered and all vehicles being associated with the target BS. Further, let k_{start} denote the block in which the first vehicle triggers the handover, and let k_{end} denote the block in which all vehicles are successfully handed over. The handover delay is then defined in terms of blocks as $K = k_{\mathrm{end}} - k_{\mathrm{start}}$, and in terms of time as $T = K T_{\mathrm{b}} + T_0$. The main aim of this paper is to analyze the handover delay, which is pursued by two objectives. The first objective is to analyze the handover delay of a legacy handover scheme, where each vehicle is handed over individually. The second objective is to propose and analyze a group handover scheme, where the handover is triggered simultaneously for all vehicles.

III. Individual Handover Scheme

In this section the message flow and triggering rule of the individual handover scheme are presented. Furthermore, the performance is analyzed in terms of the triggering and success probabilities.

A. Message Flow

The individual handover scheme is modeled according to the handover scheme used in long term evolution (LTE) [10] [11]. The message flow is modeled by the sequence of messages $\mathcal{M} = (m_{\mathrm{cmd}}, m_{\mathrm{sync}}, m_{\mathrm{resp}}, m_{\mathrm{cfm}})$, which models the *Handover Command*, *Synchronization*, *Random Access Response*, and *Handover Confirm* messages, respectively. The m_{cmd} message is sent from the source BS, while the random access channel (RACH) messages are exchanged with the target BS. The contention effects introduced by the RACH procedure are not taken into account, so for all handover messages exchanged with the target BS enough resources are assumed to be available.

B. Triggering Rule

The second element of the handover scheme is the triggering rule, which is typically based on the measured RSSs of the source and target BSs. The RSS in block k is obtained by averaging over the slots in block k. Based on the RSSs in block k the handover triggering rule determines whether a handover will start in block $k+1$. The triggering rule for triggering a handover in block k for vehicle v is given by

$$R_{\mathrm{T},v,k} - R_{\mathrm{S},v,k} > H, \quad (4)$$

where H is a preconfigured hysteresis level in dB [10]. Note that in practice alternative triggering rules may be selected, the analysis of which is left for future work.

C. Triggering and Success Probability

Each vehicle triggers a handover independently based on the RSSs of the source and target BSs. Let the handover triggering probability be defined as the probability that vehicle v triggers a handover in block k, which is given by

$$p_{\mathrm{trig},v,k} = \Pr\{R_{\mathrm{T},v,k} - R_{\mathrm{S},v,k} > H\}. \quad (5)$$

In the presented system model both the standard deviation of the shadowing and the path loss are assumed to be constant during a block, so the triggering probability is given by

$$p_{\text{trig},v,k} = Q\left(\frac{H - 10\eta\log_{10}\left(\frac{d_{\mathtt{S},v,k}}{d_{\mathtt{T},v,k}}\right)}{\sqrt{2}\sigma_{\lambda,\text{dB}}}\right), \tag{6}$$

where $Q(\cdot)$ is the tail distribution function of the standard normal distribution. The triggering probability thus increases when the vehicle moves towards the target BS.

The success probability is given by the probability that all messages in $\mathcal{M}$ are successful, which is conditioned on the handover being triggered. The error probability for a single transmission of message m is given by

$$p_{\text{e},m}(\bar{\gamma}) = 1 - \exp\left(\frac{1 - 2^{r_m/W}}{\bar{\gamma}}\right), \tag{7}$$

where $\bar{\gamma}$ is the average SNR. The success probability of message m with retransmissions is then given by

$$p_{\text{s},m}(\bar{\gamma}) = 1 - p_{\text{e},m}^{N_{\text{ret}}+1}(\bar{\gamma}). \tag{8}$$

The m_{cmd} message is transmitted from the source BS, which is successfully received by vehicle v in block k with probability

$$p_{\text{cmd},v,k} = \int_0^\infty p_{\text{s},\text{cmd}}(x) f_{\bar{\gamma}_{\mathtt{S},v,k}}(x)\, dx, \tag{9}$$

where $f_{\bar{\gamma}_{\mathtt{S},v,k}}$ is the probability density function of $\bar{\gamma}_{b,v,k}$ for $b = \mathtt{S}$. The remaining messages in $\mathcal{M}$ are communicated with the target BS, and are successfully received by vehicle v in block k with probability

$$p_{\text{rach},v,k} = \int_0^\infty \prod_{m \in \mathcal{M}\setminus\{m_{\text{cmd}}\}} p_{\text{s},m}(x) f_{\bar{\gamma}_{\mathtt{T},v,k}}(x)\, dx\,. \tag{10}$$

By combining the success probabilities of all handover messages the success probability of the individual handover can be written as

$$p_{\text{succ},v,k} = p_{\text{cmd},v,k}\, p_{\text{rach},v,k}, \tag{11}$$

which achieves its maximum between the two BSs.

IV. Group Handover Scheme

In this section a novel group handover scheme is introduced, which allows for the simultaneous and synchronized handover of a group of vehicles. The message flow and triggering rule are presented, after which the performance is analyzed in terms of the triggering and success probabilities.

A. Message Flow

The message flow of the group handover is similar to the individual handover, with the difference that the messages from the BSs are broadcasted and the message flows of the vehicles are synchronized. The group handover can thus be modeled by the same sequence of messages $\mathcal{M}$, where the m_{cmd} message is broadcasted to all vehicles and the remaining messages need to be exchanged with all vehicles individually. Since the message flow executes in a synchronous manner, the handover does not continue to the next message before all vehicles have exchanged the current message correctly. The failure of the broadcast message for a certain subset of vehicles is indicated by missing acknowledgments, after which the broadcast message is retransmitted. Each individual vehicle has a maximum number of retransmissions given by N_{ret}. As before, the contention effects introduced by the RACH procedure are not modeled.

B. Triggering Rule

The triggering rule of the group handover needs to be reformulated for multiple vehicles. As the *Measurement Control* message is now broadcasted to all vehicles, each vehicle sends back a *Measurement Report* message. Based on these reports, the source BS makes a joint handover decision in block k according to the triggering rule given by

$$\frac{1}{N}\sum_{v=1}^{N}(R_{\mathtt{T},v,k} - R_{\mathtt{S},v,k}) > H, \tag{12}$$

which is obtained by averaging the RSS differences of all vehicles.

C. Triggering and Success Probability

In the group handover all vehicles are triggered simultaneously based on the joint triggering rule. The handover triggering probability for the group handover in block k is given by

$$\begin{aligned} p_{\text{trig},k} &= \Pr\left\{\frac{1}{N}\sum_{v=1}^{N}(R_{\mathtt{T},v,k} - R_{\mathtt{S},v,k}) > H\right\}, \\ &= Q\left(\frac{NH - \sum_{v=1}^{N} 10\eta\log_{10}\left(\frac{d_{\mathtt{S},v,k}}{d_{\mathtt{T},v,k}}\right)}{\sqrt{2N}\sigma_{\lambda,\text{dB}}}\right). \end{aligned} \tag{13}$$

In the group handover each message needs to be successfully received by all vehicles, which can be seen as N independent individual handovers in parallel. The success probability conditioned on the handover being triggered can therefore be expressed as

$$p_{\text{succ},k} = \prod_{v=1}^{N} p_{\text{cmd},v,k}\, p_{\text{rach},v,k}. \tag{14}$$

The success probability thus decreases when the number of vehicles N increases.

V. Handover Delay Analysis

In this section Markov chain models are presented for both the individual and group handover, which are used to compute the handover delay distribution. In order for vehicle v to be associated with the target BS the handover needs to be triggered in block $k-1$ and the message flow needs to be successful in block k, which occurs with probability

$$p_{\text{ho},v,k} = p_{\text{succ},v,k}\, p_{\text{trig},v,k-1}. \tag{15}$$

This probability is generally not independent between blocks, since the execution of the handover in block k depends on the triggering in block $k-1$. For the sake of analytical tractability, however, it is modeled as being independent. When the handover of a vehicle fails within a block, the vehicle is assumed to be connected back to the source BS. In this case a decision can be made to automatically retrigger the handover. This implies that the source BS keeps retriggering the handover until the handover is successful. The number of handover attempts is not limited, in contrast to the maximum number of retransmissions for the message flow.

A. Markov Chain Models

In what follows, four Markov chain models are presented, which model the individual and group handover both with and without retriggering.

1) Individual Handover without Retriggering: The state space of the individual handover without retriggering contains all combinations of handed-over vehicles, and an additional state that encodes whether any of the vehicles has attempted a handover. The resulting state space can be written as

$$S = \mathcal{P}(\mathcal{V}) \cup \{\texttt{trig}\}, \tag{16}$$

where $\mathcal{P}(\mathcal{V})$ denotes the powerset of $\mathcal{V}$, so the total number of states is given by $|S| = 2^N + 1$. The initial state is $\emptyset$, while the terminal state is $\mathcal{V}$. Given the current state $x \in S$ and the next state $x' \in S$, the transition probabilities of the Markov chain are defined by

$$p_k(x, x') = \begin{cases} F^{\mathrm{c}}_{\mathrm{trig}}(\mathcal{V}) & \text{if } x = \emptyset, x' = \emptyset, \\ F^{\mathrm{c}}_{\mathrm{ho}}(\mathcal{V}) - F^{\mathrm{c}}_{\mathrm{trig}}(\mathcal{V}) & \text{if } x = \emptyset, x' = \texttt{trig}, \\ F^{\mathrm{c}}_{\mathrm{ho}}(\mathcal{V}) & \text{if } x = \texttt{trig}, x' = \texttt{trig}, \\ F_{\mathrm{ho}}(x') F^{\mathrm{c}}_{\mathrm{ho}}(\mathcal{V} \backslash x') & \text{if } x = \texttt{trig}, x' \in \mathcal{P}(\mathcal{V}) \backslash \emptyset, \\ F_{\mathrm{ho}}(x' \backslash x) F^{\mathrm{c}}_{\mathrm{ho}}(\mathcal{V} \backslash x') & \text{if } x \in \mathcal{P}(\mathcal{V}), x' \in \mathcal{P}(\mathcal{V}) \backslash \emptyset, \\ & \quad x' \supseteq x, \\ 0 & \text{otherwise,} \end{cases} \tag{17}$$

where $F_*(\mathcal{X}) = \prod_{v \in \mathcal{X}} p_{*,v,k}$ and $F^{\mathrm{c}}_*(\mathcal{X}) = \prod_{v \in \mathcal{X}} 1 - p_{*,v,k}$. The first three cases in Equation (17) correspond respectively to none of the vehicles being triggered, at least one vehicle being triggered, and none of the vehicles being handed over. The fourth case corresponds to the transition from at least one vehicle being triggered to a subset of vehicles being handed over. The fifth case corresponds to a subset of vehicles being handed over, given that a subset of vehicles is already handed over. The condition $x' \supseteq x$ ensures that once vehicles are successfully handed over they remain associated with the target BS.

2) Individual Handover with Retriggering: In the individual handover with retriggering case the vehicles that are triggered but not successfully handed over need to be tracked as well. The state space is therefore given by

$$S = \{(r, s) \mid r, s \in \mathcal{P}(\mathcal{V}), r \cap s = \emptyset\}, \tag{18}$$

where r is the set of vehicles that are triggered, and s is the set of vehicles that are successfully handed over. The number of states is given by $|S| = 3^N$. The initial state is $(\emptyset, \emptyset)$, and the terminal state is $(\emptyset, \mathcal{V})$. Given the current state $x = (r, s) \in S$ and the next state $x' = (r', s') \in S$, the transition probabilities are defined by

$$\begin{aligned} p_k(x, x') = F_{\mathrm{trig}}(r' \setminus r) F_{\mathrm{succ}}(s' \cap r) F_{\mathrm{ho}}(s' \setminus (r \cup s)) \times \\ F^{\mathrm{c}}_{\mathrm{trig}}(\mathcal{V} \setminus (r' \cup s')) F^{\mathrm{c}}_{\mathrm{succ}}(r'), \end{aligned} \tag{19}$$

if $s' \supseteq s$ and $r' \cup s' \supseteq r$, while being zero otherwise. In this expression $r' \backslash r$ contains the vehicles that transition from being not triggered to being triggered, $s' \cap r$ contains the vehicles that transition from being triggered to being successfully handed over, $s' \setminus (r \cup s)$ contains the vehicles that transition from not being triggered to being successfully handed over, $\mathcal{V} \setminus (r' \cup s')$ contains the vehicles that remain not triggered, and r' contains the vehicles that remain triggered. The condition $s' \supseteq s$ ensures that successfully handed over vehicles remain handed over, while the condition $r' \cup s' \supseteq r$ ensures that triggered vehicles either remain triggered or are successfully handed over.

3) Group Handover: In the group handover all vehicles are handed over simultaneously. The state space is therefore given by

$$S = \{\texttt{none}, \texttt{trig}, \texttt{done}\}, \tag{20}$$

where `none` corresponds to none of the vehicles being handed over, `trig` encodes a group handover attempt, and `done` denotes all the vehicles being successfully handed over. The initial state is given by `none`, and the terminal state is given by `done`. Given the current state $x \in S$ and the next state $x' \in S$, the transition probabilities are defined by

$$p_k(x, x') = \begin{cases} 1 - p_{\mathrm{trig},k} & \text{if } x = \texttt{none}, x' = \texttt{none}, \\ p_{\mathrm{trig},k}(1 - p_{\mathrm{succ},k}) & \text{if } x = \texttt{none}, x' = \texttt{trig}, \\ p_{\mathrm{trig},k} p_{\mathrm{succ},k} & \text{if } x = \texttt{none}, x' = \texttt{done}, \\ 1 - \alpha_k & \text{if } x = \texttt{trig}, x' = \texttt{trig}, \\ \alpha_k & \text{if } x = \texttt{trig}, x' = \texttt{done}, \\ 1 & \text{if } x = \texttt{done}, x' = \texttt{done}, \\ 0 & \text{otherwise,} \end{cases} \tag{21}$$

where $\alpha_k = p_{\mathrm{trig},k} p_{\mathrm{succ},k}$ without retriggering, and $\alpha_k = p_{\mathrm{succ},k}$ with retriggering. The cases in Equation (21) correspond respectively to the handover being not triggered, being triggered, being triggered and successful, remaining triggered, being successful, and remaining successful.

B. Handover Delay Distribution

The four Markov chain models can be used to calculate the handover delay distribution. This is done by exploiting the fact that each of these chains is an absorbing Markov chain with a single initial state and a single terminal state. The handover delay is thus given by the time until absorption, which has a discrete phase-type distribution [12]. However, the studied Markov chains present two additional challenges. First, the chains are time-inhomogeneous. Second, the handover delay is measured starting from the transition out of the initial state.

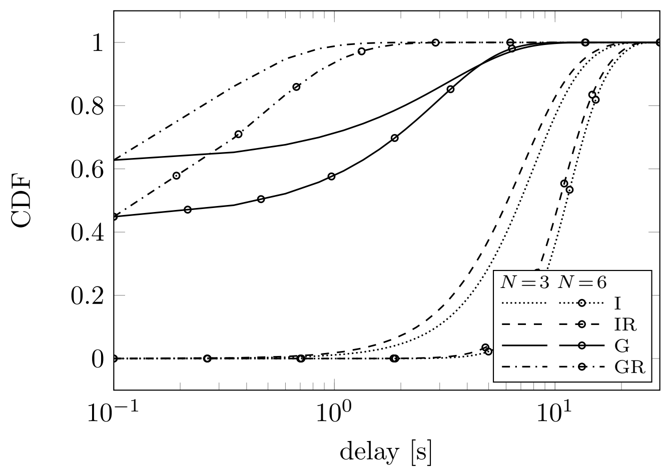

Figure 4. Handover delay CDF for varying number of vehicles using the individual handover (I), individual handover with retriggering (IR), group handover (G), and group handover with retriggering (GR).

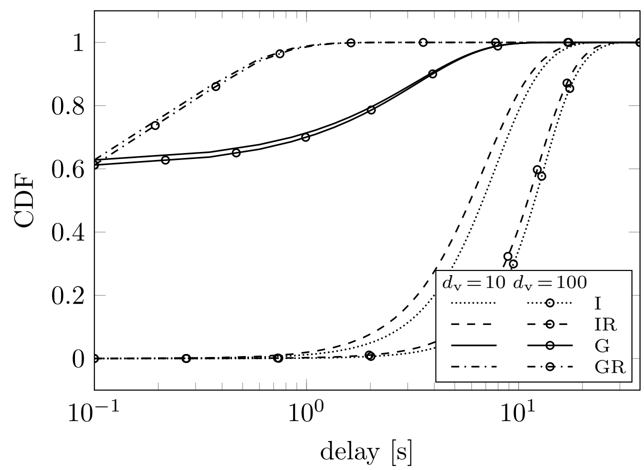

Figure 5. Handover delay CDF for varying vehicle distances using the individual handover (I), individual handover with retriggering (IR), group handover (G), and group handover with retriggering (GR).

Based on the introduced transition probabilities a time-varying transition matrix P_k can be constructed. This matrix can be partitioned as

$$P_k = \begin{bmatrix} z_{1,k} & q_{1,k} & z_{|S|,k} \\ & Q_k & q_{|S|,k} \\ & & 1 \end{bmatrix}, \tag{22}$$

where $z_{1,k}$ and $z_{|S|,k}$ are scalars respectively representing the probabilities of remaining in the initial state and transitioning from the initial to the terminal state. The square matrix Q_k of size $|S|-2$ represents the transition probabilities for the intermediate states without considering the initial and terminal states. Finally, the row vector $q_{1,k}$ of size $|S|-2$ represents the transition probabilities from the initial state to the intermediate states, while the column vector $q_{|S|,k}$ of size $|S|-2$ represents the transition probabilities from the intermediate states to the terminal state. The probability mass function (PMF) of k_{start} can then be written as

$$f_{k_{\text{start}}}(k) = (1 - z_{1,k}) \prod_{l=0}^{k-1} z_{1,l}, \tag{23}$$

which is the product of the probability that none of the vehicles are successfully handed over before k_{start}, and the probability that at least one vehicle is triggered at k_{start}. The block in which all vehicles are handed over is given by k_{end}. The PMF of k_{end} conditioned on k_{start} is given by

$$f_{k_{\text{end}}|k_{\text{start}}}(k \mid l) = \begin{cases} \frac{z_{|S|,l}}{1-z_{1,l}} & \text{if } k = l, \\ \frac{q_{1,l}}{1-z_{1,l}} \left(\prod_{m=l+1}^{k-1} Q_m \right) q_{|S|,k} & \text{if } k > l, \\ 0 & \text{otherwise,} \end{cases} \tag{24}$$

where $\frac{q_{1,l}}{1-z_{1,l}}$ represents the normalized initial distribution of the intermediate states. The unconditional PMF of k_{end} can then be obtained by marginalizing out k_{start} which gives

$$f_{k_{\text{end}}}(k) = \sum_{l=0}^{\infty} f_{k_{\text{end}}|k_{\text{start}}}(k \mid l) f_{k_{\text{start}}}(l), \tag{25}$$

while the PMF of K is given by

$$f_K(k) = \sum_{l=0}^{\infty} f_{k_{\text{end}}|k_{\text{start}}}(k + l, l) f_{k_{\text{start}}}(l). \tag{26}$$

The distribution of the handover delay $T = KT_{\text{b}} + T_0$ can be obtained through the distribution of K.

VI. Numerical Evaluation

In this section the performance of the individual and group handover is numerically evaluated. A vehicle platoon of $N = 3$ vehicles is considered, which is assumed to drive at a constant velocity of $20\,\text{m/s}$. The distances in Figure 2 are given by $d_{\text{S,T}} = 1000\,\text{m}$, $d_{\text{r}} = 200\,\text{m}$, and $d_{\text{v}} = 20\,\text{m}$. The path loss and the shadowing are modeled according to the line-of-sight C1 propagation scenario of the WINNER II channel models, where the carrier frequency is chosen to be $2\,\text{GHz}$ [13]. The remaining communication system parameters are given by $W = 10\,\text{MHz}$, $P_{\text{tx}} = 20\,\text{dBm}$, and $\sigma_n^2 = -90\,\text{dBm}$. Additionally, an SNR gap of $6\,\text{dB}$ is introduced which captures the channel estimation, modulation, and encoding losses. The duration of a block is assumed to be $T_{\text{b}} = 250\,\text{ms}$, while the slot duration is chosen to be $T_{\text{s}} = 1\,\text{ms}$. The hysteresis parameter is assumed to be $H = 2\,\text{dB}$. The handover messages are assumed to have a fixed packet size of $600\,\text{bytes}$. Furthermore, the message flow duration is assumed to be $T_0 = 100\,\text{ms}$, and the maximum number of retransmissions is set to $N_{\text{ret}} = 1$. With this parameterization, the presented results are validated using extensive Monte Carlo simulations.

The CDF of the handover delay T is shown in Figure 4 for different number of vehicles. It is clear that the group handover reduces the handover delay considerably in comparison to the individual handover scheme. The performance of the individual

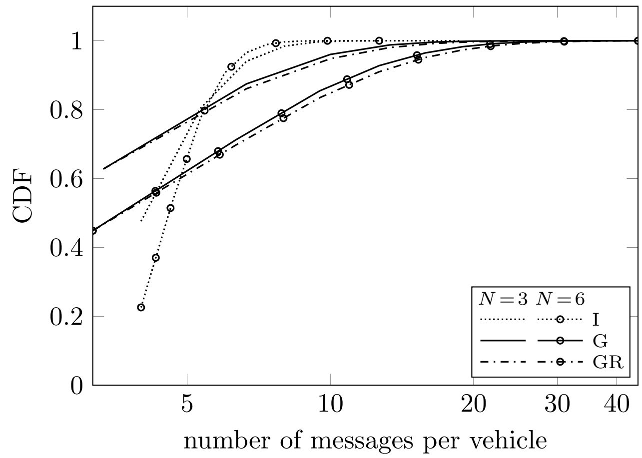

Figure 6. Number of messages per vehicle CDF for varying number of vehicles using the individual handover (I), group handover (G), and group handover with retriggering (GR).

handover is dominated by the performance of the triggering rule, since each vehicle needs to be triggered individually. The group handover, on the other hand, is dominated by the performance of the message exchange, since the messages for all vehicles need to be successful in the same block. Increasing the number of vehicles thus impacts both handover schemes. However, the performance of the group handover can be improved considerably by retriggering the handover after a failure, while this results only in a small improvement for the individual handover. Similar conclusions can be drawn when considering the CDF of the handover delay for different vehicle distances, as shown in Figure 5. The handover delay of the individual handover increases when the distance between the vehicles increases, due to the increased spread in handover triggering times. The handover delay of the group handover increases significantly less, since the performance is less dependent on the triggering time instant.

An important consideration is the potential cost of the improved handover delay performance. Figure 6 shows the CDF of the number of messages per vehicle, which are obtained from Monte Carlo simulations. Only the individual handover without retriggering is plotted, since the performance with retriggering is similar. When the group handover fails all messages need to be retransmitted, which leads to a larger messaging overhead in comparison to the individual handover. Furthermore, the messaging overhead of the group handover increases when the number of vehicles increases. The individual handover on the other hand scales well when the number of vehicles increases. It is clear that a trade-off exists between the handover delay and the messaging overhead.

VII. Conclusions

Both the individual and group handover schemes were modeled as discrete-time Markov chains. Analytical expressions for the stochastic handover delay distribution were derived. Numerical results showed that the group handover significantly decreases the handover delay in comparison to the individual handover. Furthermore, the group handover was shown to scale well when the number of vehicles increases. The increased performance of the group handover was shown to come at the price of a larger messaging overhead.

The presented results open up many possibilities for future work. The considered numerical evaluation requires a more thorough investigation. Furthermore, the performance of the handover can be improved by optimizing the hysteresis parameter of the triggering rule. Additionally, other types of triggering rules can be investigated. The presented Markov chain models can also be extended to include a maximum number of retriggering attempts. The precise impact of the handover on the control system can be investigated by modeling the interactions between the control system and the mobile network.

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