Velocity-aware Antenna Selection in Predictor Antenna Systems

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Abstract—Moving relay (MR), which is a candidate solution for supporting in-vehicle users, has been investigated in different studies. Due to the mobile nature of the MR, acquiring channel state information at the transmitter side (CSIT) is challenging because of the fast-changing environment around the vehicle. On top of an MR, one can use predictor antenna (PA), i.e., an additional antenna in front of the receive antenna (RA), to obtain CSIT, and recent works have investigated the benefits of such a setup. PA-aided CSIT acquisition normally works with the help of different content information such as the location and the velocity of the MR. In this paper, we study the effect of velocity awareness on the PA system, and develop adaptive antenna selection schemes in PA-assisted MRs. Results show that, compared to no-CSIT on the PA system, and develop adaptive antenna selection schemes schemes, a velocity-aware antenna selection-based PA system can improve the end-to-end throughput by an order of magnitude.

Index Terms—6G, channel estimation, context-aware communication, integrated access and backhaul (IAB), moving relay, predictor antenna, throughput, vehicle-to-everything (V2X), wireless backhaul.

I. INTRODUCTION

As a complement to fixed relays, moving relay (MR) has been discovered to be a candidate method to serve mobile users [1], [2]. MRs can improve the quality of service (QoS) of in-vehicle users by reducing the vehicle penetration loss (VPL) and performing group handover. One main challenge for MR is however, how to obtain accurate channel state information at the transmitter side (CSIT) because the relay itself is naturally moving. To overcome this issue, the concept of predictor antenna (PA) has been first proposed in [3] in which two sets of antennas are deployed on top of a vehicle. The PA positioned in the front is used for predicting the CSIT for the antennas behind it, referred to as receive antenna (RA), who will later encounter a similar channel as the PA encountered several time slots before.

Various testbed-based studies have validated the PA concept together with advanced technologies such as massive multiple input multiple output (MIMO) [4] and low-pass filtering [5] at high velocity. It is shown in [6] that the PA system can be beneficial in both time division duplex (TDD) and FDD (F: Frequency) setups with line-of-sight (LoS) and NLOS (N: non) channels. Moreover, using Kalman filtering to interpolate for the TDD uplink estimation is studied in [7].

The PA system, however, may face spatial mismatch, i.e., the RA does not reach the same spatial point as the PA, due to varying vehicle velocity or the processing delay at the base station (BS) [2], [8]. That is, for the acquired CSIT to be accurate, the RA needs to be as close as possible to the point where the PA has estimated the channel. Such an alignment scheme, and/or alternative methods (e.g., rate adaptation in [8]) require knowledge of vehicle velocity, control loop time, as well as antenna spacing. [8] focuses on SISO (S: Single) setup and proposes analytical models of the PA system with spatial mismatch, while the effect of multiple antennas at both transceiver sides has not been fully investigated.

In this paper, we first review the PA concept and give a comprehensive literature study of the PA. Then, we study the data transmission efficiency and reliability of PA systems with multiple antennas at the MRs. Specifically, we investigate the effect of knowing the velocity on the system performance. Also, we design an adaptive scheme to choose the best RA based on the vehicle velocity, such that spatial mismatch is minimized. Finally, we study the effect of different parameters such as the antennas distance and the vehicle velocity on the performance of PA systems. The results show that, using adaptive antenna selection and rate adaptation, there is potential for improving the performance of the PA system.

II. PA CONCEPT AND LITERATURE REVIEW

Thanks to the flexible deployment and the VPL elimination, MR has the potential to become to one important component in mobile networks [1], [2], [9]. The benefit of deploying MR can be mainly divided into two aspects:

- Eliminating VPL for in-vehicle users: The users inside the vehicles such as commuters normally expect similar, uninterrupted mobile service as they have in home or office. However, vehicle itself forms a natural blockade to the radio signal propagation which leads to high VPL [10]. Thus, VPL can drastically degrade the signal strength and as a result, affect the received QoS remarkably. Results in [10] reveal that the VPL is around 25 dB at sub-6 GHz and it could definitely be worse at higher frequencies such as millimeter wave (mmw) bands, due to the fact that mmw signals are more sensitive to propagation blockers.

Using MR with both outside-vehicle and inside-vehicle modules, the VPL can almost be eliminated and the users
inside the vehicle could experience a nearly pure LoS condition [1].

- **Increasing the coverage of cellular networks for out-vehicle users**: As one type of relay with relatively easy deployment, MR can also be used for extending the coverage of macro-cell network by cooperative relaying [11], [12]. By joint transmission with macro-cell BSs, the MR-aided system can remarkably improve the coverage probability [11]. Indeed, compared to serving the in-vehicle user equipments (UEs), data transmission to out-vehicle UEs is of lower priority, unless for, e.g., public safety use-cases where the MR is used for coverage extension.

In both applications of the MR, outside-vehicle backhaul links have attracted more attention from researchers than inside-vehicle access links since the later one is normally LoS with low design complexity. Also, wireless backhaul is more suitable to deploy in outdoor MRs because of its flexibility and low cost. Naturally, the design of the wireless backhaul link becomes the bottleneck of the system capacity in order to serve many MR-assisted users [1].

Using advanced transmission schemes at the BS side such as MIMO, Coordinated Multi-Point (CoMP) joint transmission, and different rate allocation algorithms can improve the performance of the MR backhaul link. Among all these techniques CSIT plays an important role since the quality of CSIT affects the system performance directly. On the other hand, with moving vehicle as MR, the environment around changes quickly and the channel estimation delay makes the CSIT at the BS side outdated quickly. The situation becomes more severe at higher moving speed and frequency bands.

One can use diversity-based transmission schemes at the cost of extra resources. Also, using location information can help with CSIT estimation but the location uncertainty needs to be handled carefully [13]. Alternatively, using channel predictors such as Kalman or Wiener can obtain the prediction range of 0.1-0.3 times the wavelength, which is sufficient for low/moderate speed vehicles or pedestrians at cm-wave carrier frequencies [3]. Nevertheless, these predictors become inefficient when speed and frequency increases. Compensate by increasing the number of pilots and perform channel interpolation would introduce unrealistic overhead.

As one promising setup aiming at acquiring better CSIT condition for MRs, the PA setup was firstly proposed in 2012 [3], where two groups of antennas are mounted on the top of a vehicle. The front one w.r.t. moving direction is dedicated as PA(s) which is(are) used for channel sensing and estimation and the obtained channel information is sent back to the BS. Then, in the next time slot(s), the vehicle moves forward and the antennas behind PA, denoted as RAs, would finally reach the same spatial point as the PAs. In this way, if the processing delay at the BS is designed properly based on, e.g., wavelength, antenna separations and vehicle speeds, the RAs could receive the signal at the point where the PA used to estimate the channel. By doing so the CSIT for the RAs can achieve high accuracy and as a result, the system is capable of utilizing various advanced transmission schemes to improve the QoS.

In [3], compared with Kalman filter-based prediction, it is shown that a PA-assisted system can give decent CSIT accuracy in both LoS and non-line-of-sight (NLoS) conditions with prediction range being around $\lambda$ and $\lambda/2$, respectively, with $\lambda$ being the wavelength. Following [3], different testbed-and simulation-based studies have investigated and revealed the potential of the PA. [1] introduces dedicated MR links with deployment of the PA, and studies the effect of VPL by system-level simulations. Using multiple antennas at the BS, [14] design a downlink multiple input single output (MISO) system with PA interpolation, in order to mitigate residual beamforming (BF) mis-pointing. From antenna design perspective, [15] focus on the PA-RA correction and performance coupling compensation to enhance the performance. Using antenna coupling compensation, at least three times $\lambda$ can be predicted with accuracy above 96% cross-correlation between the PA and RA channels [13]. With early development of 5G, [16] investigates optimal required number of PAs/RAs on the top of a vehicle in terms of spectrum efficiency and power, at both 1.2 and 3.5 GHz.

Besides modeling and simulations, testbed-based research studies have been performed to validate the feasibility of the PA concept. Part of [15] is dedicated to the demonstration of the proposed coupling compensation in downtown Dresden, Germany. Results in [15] indicate the superior performance of using quarter-wavelength monopoles rather than half-wavelength dipoles in the PA system. Then, in 2017, a testbed study was performed at 2.53 GHz in Dresden, verifying that the prediction horizon of the PA system can be at least up to three times the wavelength [5]. As an extension of [5], [6] proposes interpolation-based PA estimation scheme and verifies it with practical measurements. Finally, with massive MIMO, [4] evaluates the performance of the PA system at 2.18 GHz, and the large gains on the signal-to-interference ratio is a promising indication of the feasibility of utilizing the PA in multiple antenna systems.

Given that 1) the PA system is highly sensitive to spatial mismatch, i.e., the RAs could not reach the same point as the PAs; 2) The PA system does not have analytical model to obtain tractable evaluations, recent studies [2], [8], [17]–[21] address these problem and further clarify the potential of the PA system. [17] investigates the spatial mismatch problem in the PA system, and proposes a tractable channel model to evaluate the effect of spatial variation with rate adaptation. Then, the model in [17] has been further evaluated in [8] with temporal evolution of the channel. With two sets of antennas on top of a vehicle, the potential of involving PA partially into the transmission have been studied in [18], [19], where hybrid automatic repeat request (HARQ) is combined with system and optimal power [18] and average rate [19] of the HARQ-based PA system are investigated respectively. Considering finite block-length transmission, [20] studies the effect of the codeword length on the average throughput and error probability. Also, [2] reviews the recent progress on the
Moving Vehicle

Fig. 1. The illustration of the PA system with spatial mismatch.

PA study and proposes adaptive/non-adaptive delay methods to be applied in the PA system with spatial mismatch. The role of the PA in the development of MR and integrated access and backhaul (IAB) are also summarised. Finally, [21] extends the PA concept to multiple vehicles and investigates the potential of using PA for dynamic blockage avoidance in cooperative internet-of-vehicle networks.

In [2], [8], [17]–[21], the speed of vehicle is assumed to be known at the BS, which may not be practical in real applications. Alternatively, using the speed information at the vehicle side and perform antenna selection could potentially enhance the PA system at the presence of spatial mismatch.

III. MODEL AND METHOD

Considering a setup illustrated in Fig. 1 a moving vehicle is deployed with one PA and multiple RAs on its top. The separation between the PA and i-th RA is $d_{a,i}$. First, let’s consider the case with one RA to introduce the model, i.e., the separation of the PA and the RA is $d_a$, as used in, e.g., [8]. At time $t_1$, the PA estimates the channel and sends the channel information back to the BS. Then, at $t_2$, depending on, e.g., $d_a$, speed $v$, and the processing time $t_{BS}$ at the BS, the RAs may end up in different places. In this way, the mismatch distance $d$ between

1. the place where the PA estimates the channel, and
2. the point where the RA actually reaches at $t_2$

can be expressed by

$$d = |vT - d_a|, \quad (1)$$

where $T = t_2 - t_1$. Denote $y$ as the received signal at the RA, and it is given by

$$y = \sqrt{ph}x + z. \quad (2)$$

Here, $P$ is transmit power, and $x$ represents transmit signal with unit energy. $z \sim CN(0,1)$ is the independent and identically distributed complex Gaussian noise added at the receiver side. Using the same method as in [8]

$$h = \sqrt{1 - \sigma^2}\hat{h} + \sigma q \quad (3)$$
to model the BS-RA channel $h$ as a function of the BS-PA channel $\hat{h}$ and $q \sim CN(0,1)$. Here, $\sigma$ is a parameter which is a function of $d$ in (1), and larger $\sigma$ represents bigger spatial mismatch. Defining $g = (1 - \sigma^2)|\hat{h}|^2$ with $h \sim CN(0,1)$ and $\hat{g} = |\hat{h}|^2$, the CDF of $g$ is given by

$$F_{g|\hat{g}}(x) = 1 - Q\left(\sqrt{\frac{2\hat{g}}{\sigma^2}}, \sqrt{\frac{2x}{\sigma^2}}\right). \quad (4)$$

Here, $Q(\cdot)$ represents Marcum-Q function.

The goal is to maximize the outage/error-limited throughput which is defined as

$$\eta = \mathbb{E}\{\eta g(r_{i|g}^{opt})\}, \quad (5)$$

with

$$r_{i|g}^{opt} = \arg\max_{r_{i|g} \geq 0} \{1 - \Pr\{\log(1 + gP) < r_{i|g}\}\} \cdot r_{i|g}. \quad (6)$$

In [8], [17], different analytical methods of solving (6) are presented, and results indicate that while rate adaptation can mitigate spatial mismatch and provide notable throughput gain compared to no CSIT, the throughput is still very sensitive to the speed variation with one RA.

Given that the speed is known at the receiver side, it is possible to add additional RAs and perform antenna selection to obtain better performance. The proposed velocity-aware antenna selection scheme is summarized in Algorithm 1. Here, we assume that in each time slot the velocity is known at the receiver side. In this way, from (1) the mismatch distance for each RA $d_i$ can be calculated. Then, we evaluate the expected throughput (5) for each RA. Finally, the best RA can be picked with the highest throughput, which can be expressed as

$$\eta^{opt} = \max_i \eta_i, \quad (7)$$

where $\eta$ is given by (5).

IV. SIMULATION RESULTS

In the simulations, we study the performance of the PA system with a focus on the effect of speed variation on the system performance. We set moving time $T = 5$ ms and carrier frequency 2.68 GHz. In Figs. 2[4] we study the performance loss of one RA system due to spatial/speed mismatch in terms of required SNR for given average throughput, throughput with FBL codewords [20], and average error probability under FBL [20], respectively, with antenna separation set to 1.5 times the wavelength. Then, in Figs. [5][7] the detailed performance of the proposed antenna selection scheme is presented.
Fig. 2 shows the required transmit SNR for given throughput threshold as a function of different speed. Here, the throughput threshold is set to 5 npcu. The case with PA and rate adaptation is compared to the performance with full CSIT and no CSIT. Also, in Fig. 3, considering FBL codewords, throughput is calculated for both cases with/without the PA for different spatial mismatches. Here, \( \sigma \) is a function of the mismatch distance \( d \) and larger \( \sigma \) represents higher mismatch. Similarly, focusing on average error probability, Fig. 4 shows how it changes with transmit SNR with codeword length set to 300.

Then, applying Algorithm 1, Fig. 5 studies the throughput as a function of vehicle speed for one, three, and five RAs, respectively. In the case with one RA, \( d_a = 1.5 \lambda \), and for three RAs \( d_{a,1}, d_{a,2}, \) and \( d_{a,3} \) are set to 1.6, 1.5 and 1.4 \( \lambda \), respectively. For five RAs the antenna separations are 1.62, 1.5, 1.44, and 1.38 \( \lambda \). Using similar settings, i.e., the distance between RAs are the same for three and five RAs, Fig. 6 indicates the best RA index for different \( d_{\text{am}} \), which is the distance between the PA and the RA in the middle. Finally, in Fig. 7 the average throughput for the considered speed range (100-140 km/h) are plotted for the cases with different number of RAs and no CSIT. The antenna separations are the same as in Figs. 5-6.

According to the simulation figures, the following conclusions can be drawn:

- With spatial mismatch, considerable performance loss can be observed. For instance, the required SNR increases with larger mismatch and eventually becomes equal to...
V. CONCLUSIONS

We reviewed the PA concept and recent testbed- and theoretical-oriented studies on the PA. With promising progress on the PA studies, it has emerged as one promising enabler for MR and moving IAB nodes in next generation of mobile networks. Dealing with the speed/spatial mismatch problem, we proposed a novel antenna selection scheme to fully utilize the velocity information and make the system more robust to speed variations. The simulation results further clarified the effect of mismatch from different perspectives, and our proposed velocity-aware antenna selection scheme shows notable performance gains with multiple RA deployed at the vehicle side.

ACKNOWLEDGEMENT

This work was supported in part by VINNOVA (Swedish Government Agency for Innovation Systems) within the VINN Excellence Center ChaseOn and in part by the European Commission through the H2020 project Hexa-X (Grant Agreement no. 101015956).

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