Antenna Controller for Low-latency and High Reliability Robotic Communications over Time-varying Fading Channels

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***Abstract*—In this paper we consider the problem in which a single antenna mobile robot (MR) is required to maintain reliable communication with a base station (BS) while following a given trajectory. The wireless communication channel is assumed to experience time-varying small-scale fading with time-varying coherence time. To achieve high reliability and low latency of the communication link, compensation for the small-scale fading is required. Since the MR has to stay on the predefined trajectory, we propose to compensate for the fading by continuously adjusting the position of the antenna on a revolving platform onboard the MR. This is done by a closed-loop antenna controller which optimises the position of the antenna at all times without modifying the trajectory to be followed by the MR. Results show that this technique can effectively compensate for the small-scale fading without introducing delays in data reception.**

***Index Terms*—Mobility diversity, small-scale fading, antenna controller, robotics.**

I. Introduction

Recently there has been a growing interest in wireless communications problems related to MRs equipped with wireless transceivers (e.g., [1]- [5]). In this context, two important problems have attracted significant interest. The first problem consists of designing trajectories for MRs which take into account simultaneously the energy spent in motion and communications related metrics and/or constraints [2], [4], [16], [13]. The second problem consists of controlling the position of a MR to compensate for the small scale fading and thus improve communication performance [1] [1], [6], [7]. These type of problems differ from classical communication problems in that in order to be solved they often require knowledge from both communication and control theories [1], [11], [14].

In this paper we consider a MR equipped with a revolving platform with a single antenna fixed on it. In addition, the MR periodically receives from a BS (also equipped with a single antenna) critical data necessary to follow a certain trajectory and perform certain time-sensitive tasks. This data is transmitted through user datagram protocol (UDP) packets via a wireless channel experiencing time-variant, small-scale fading with a time-variant coherence time which on occasions can take large values while on other occasions it can take values just slightly above the duration of the UDP packet, (see section III-A).

[1]This technique is sometimes referred to as mobility diversity.

Due to the time-critical nature of the mission of the MR (the tasks to be performed and the trajectory to be followed) it is necessary to ensure a very low bit error rate (BER) as well as low latency in the reception of the payload. Otherwise the MR might not be able to follow the necessary trajectory and perform the tasks required by the BS within the appropriate time. Hence small-scale fading must be compensated for to ensure a low BER, and this must be done without introducing any delay in the reception of the payload. Further, this must be achieved without interfering with the MR trajectory.

Since the channel is time-variant, we could try to compensate for the small-scale fading by using classical temporal diversity techniques [10], [19]. However, since the coherence-time is in general larger than the duration of the UDP packet duration (and can also reach very large values), this kind of diversity would introduce large delays which would impede the MR in fulfilling its mission. Another approach to solve this problem is to use the principle of mobility diversity [11]. However, up until now, all the techniques described in the literature which make use of this principle require a time-invariant channel and hence are not applicable to the particular problem considered in this paper. In [9], the authors use a static turntable with an antenna mounted on it to take advantage of the small-scale fading. This system works by moving the antenna while measuring the channel gain received and then stopping at a position where the channel gain is large enough. The problem with this approach is that while the system searches for a good position many packets are lost due to the deep fades encountered. Other mobility diversity techniques require altering the trajectory of the MR (which is not allowed in our problem) by making strategic stops at certain locations ([6], [15]) where the channel is large enough. In addition these solutions and some others found in the literature implementing the principle of mobility diversity (e.g. [12], [11] and [7]) require a time-invariant wireless channel and hence are not applicable to our problem.

Therefore in order to solve the problem considered in this paper, we propose to develop a closed-loop controller which will constantly optimise the position of the antenna, thereby providing a good SNR during the reception of all the UDP packets transmitted via a time-variant fading channel with time-variant coherence time. In addition, this controller will

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not introduce any delay in the payload allowing low latency communication with low BER. Furthermore, this controller will only modify the position of the antenna on the revolving platform but will not alter the trajectory of the MR, unlike the existing mobility diversity techniques [6].

The paper is organised as follows. In section II we present the mathematical model of the MR and of the wireless communications channel. Then the closed-loop controller for the antenna is developed in III while simulation results are presented in section IV and finally conclusions are given in section V.

II. System Model

A. The mechanical model

As mentioned before, we consider a MR equipped with a single antenna mounted on a revolving platform on the top of the MR. The distance from the antenna to the center of the revolving platform is denoted by ρ. Now, let us denote by $\mathcal{I}_B$ the coordinate system with origin in the BS and axes given by the set of orthonormal vectors $\{\widehat{\mathrm{e}}_i\}_{i=1}^2$. Unless explicitly stated otherwise, all the vectors (and sets of vectors) mentioned in this paper will be assumed to be represented within this coordinate system.

We will assume that the geometrical center of the MR is also the center of the revolving platform denoted by vector $\mathbf{p}(t)$ while the position of the antenna is denoted by vector $\mathbf{q}(t)$. The orientation of the MR ($\phi(t)$) is defined as the angle of $(\mathbf{f}(t)-\mathbf{p}(t))$ where vector $\mathbf{f}(t)$ denotes the front of the MR. Let us also refer to the relative position of the antenna with respect to $\mathbf{p}(t)$ as:

$$\mathbf{q}_r(t) \triangleq \mathbf{q}(t) - \mathbf{p}(t). \tag{1}$$

Now, let us define a new coordinate system $\mathcal{I}_M(t)$ with its origin fixed on the center of the revolving platform $\mathbf{p}(t)$ and with orthonormal axes defined with respect to the MR's orientation:

$$\begin{aligned} \widehat{\mathbf{e}}_3(\phi(t)) &= [\cos(\phi(t)) \;\; \sin(\phi(t))]^{\mathrm{T}}, \\ \widehat{\mathbf{e}}_4(\phi(t)) &= [-\sin(\phi(t)) \;\; \cos(\phi(t))]^{\mathrm{T}}, \end{aligned} \tag{2}$$

where the axis vectors (2) of $\mathcal{I}_M(t)$ are themselves represented within $\mathcal{I}_B$. Then, $\mathbf{q}_M(t)$ (i.e., $\mathbf{q}(t)$ expressed within the coordinate system $\mathcal{I}_M(t)$) is related to $\mathbf{q}(t)$ according to the following linear transformation[2]:

$$\mathbf{q}_M(t) = \mathbf{R}(\phi(t))\left(\mathbf{q}(t) - \mathbf{p}(t)\right), \tag{3}$$

where the rotation matrix $\mathbf{R}(\phi(t)) = [\widehat{\mathbf{e}}_3(\phi(t)) \; \widehat{\mathbf{e}}_4(\phi(t))]$. In addition, since the antenna is mounted on a rotating platform then $\mathbf{q}_M(t)$ is related to the control signal $u(t)$ as:

$$\begin{aligned} \dot{\omega}(t) &= u(t), \\ \mathbf{q}_M(t) &= \rho\left[\cos\left(\omega(t)\right), \; \sin\left(\omega(t)\right)\right]^{\mathrm{T}} \end{aligned} \tag{4}$$

[2]Note that because the origin and axes of the coordinate system $\mathcal{I}_M(t)$ move with respect to the coordinate system $\mathcal{I}_B$. So, if $\mathbf{q}(t)$ is a constant then $\mathbf{q}_M(t)$ may not be constant. The opposite also holds.

where $|u(t)| \leq U_{max}$ is the signal controlling the motor of the rotating platform. Finally, let us denote by $\mathcal{A}_M(\mathbf{q}_M(t), \tau)$ the set of all positions[3] reachable by the antenna in a duration τ when departing from $\mathbf{q}_M(t)$. We will refer to $\mathcal{A}_M(\mathbf{q}_M(t), \tau)$ as the *antenna reachability space*.

B. The communications model

The MR periodically receives UDP packets from the BS with period T and packet duration of αT with $\alpha \in (0, 1)$. The MR operates in a cluttered static environment without line of sight between the MR and the BS. In addition, we assume that the communication is performed using narrowband signals. Thus, we assume that the wireless channel experiences flat Rayleigh small-scale fading. The channel model from the communication between the BS to the MR, as function of $\mathbf{q}(t)$, is then:

$$z(t) = x(t)s(\mathbf{q}(t))h(\mathbf{q}(t)) + n(t) \tag{5}$$

where $x(t)$ is the signal transmitted by the BS; $n(t)$ is the additive white Gaussian noise AWGN; $z(t)$ is the signal received by the MR; $s(\mathbf{q}(t))$ is the shadowing term which we assume to be known[4]; and $h(\mathbf{q}(t))$ is the small-scale fading term. Note that since the environment is assumed to be static and the position of the BS is also assumed to be constant then the small-scale fading term in (5) depends only on the position of the MR's antenna $\mathbf{q}(t)$. We will assume Jakes' model [18] for the small-scale fading term and so $h(\mathbf{q}(t)) \sim \mathcal{CN}(0, \sigma_n^2)$ and its normalized spatial correlation is:

$$\mathbb{E}[h(\mathbf{q}_1)h^*(\mathbf{q}_2)] = J_0\left(\frac{2\pi\|\mathbf{q}_1 - \mathbf{q}_2\|_2}{\lambda_c}\right) \tag{6}$$

where λ_c is the wavelength of the carrier used by the BS; $\mathbf{q}_1$ and $\mathbf{q}_2$ are any two points and $J_0(\cdot)$ a the Bessel function of zero-order and first kind.

III. Antenna controller

The main objective of the closed-loop antenna controller is to compensate for the small-scale fading of the wireless channel. It operates as follows: During $t \in [nT, (n+\alpha)T)$ the controller maintains the position of the antenna constant (i.e., constant $\mathbf{q}_M(t)$). During that period of time the MR receives the nth UDP packet, and uses the header of this packet to estimate the wireless channel. Then the controller uses this channel estimate to calculate the best position of the antenna in order to maximize the expected value of the SNR during the reception of the next UDP packet, i.e., it optimizes $\mathbf{q}_M((n+1)T)$. Then during $t \in [(n+\alpha)T, (n+1)T)$ the controller moves the antenna to the optimum position calculated. Then the process is repeated.

Before we proceed to develop the controller we will first demonstrate that although $h(\mathbf{q}(t))$ is time-independent and

[3]Expressed within $\mathcal{I}_M(t)$.

[4]This term can be estimated using a technique like the one presented in [17]. Hence, since it can be estimated and since the main focus of this paper is on the compensation of the small-scale fading we will not consider the shadowing term in the rest of the paper.

depends only on $\mathbf{q}(t)$ the channel observed by the communications system is indeed time-variant with varing coherence time, and we will present a detailed mathematical definition for the coherence time. Then we develop the controller taking as a basis the mobility diversity technique that we developed in [1].

A. Relative time-variance of the wireless channel

Even though the environment is static and $h(\mathbf{q})$ in (5) is time-invariant and depends only on $\mathbf{q}(t)$ we proceed to demonstrate that the channel observed by the communications system is indeed time-variant. This comes from the fact that the communications system, in this paper, cannot fully control $\mathbf{q}(t)$ since it can only control the rotating platform where the antenna is located but cannot alter the MR's trajectory. So now we proceed to demonstrate this property and present a mathematical definition for the coherence time.

First, we note that $\mathbf{q}(t)$ is the MR antenna's position viewed from the perspective of an observer located at the BS while $\mathbf{q}_M(t)$ is the position of the MR antenna's position viewed from the perspective of an observer located at the center of the MR. Note also that while the communications system cannot fully control $\mathbf{q}(t)$ it can fully control $\mathbf{q}_M(t)$ by means of the rotating platform (see (4)). So, let us re-write the small-scale fading term in (5) as a function of $\mathbf{q}_M(t)$:

$$\begin{aligned} h(\mathbf{q}(t)) &= h(\mathbf{p}(t)+\mathbf{q}_r(t)), \\ &= h(\mathbf{p}(t)+\mathbf{R}^{-1}(\phi(t))\mathbf{q}_M(t)). \end{aligned} \tag{7}$$

Since the communication system is not allowed to modify the trajectory of the MR, $\mathbf{p}(t)$ and $\phi(t)$ are uncontrollable time-variant processes from the perspective of the communications system. Hence although the small-scale fading term observed from the BS's perspective is time-invariant (since it depends only on $\mathbf{q}(t)$) the same small-scale fading term becomes time-variant when observed by the communications system due to the uncontrollable (for the communications system) processes mentioned above $\mathbf{p}(t)$ and $\phi(t)$. To denote this time dependence we rewrite (7) as $h_q(\mathbf{q}_M(t), t)$.

Now, departing from (6), we can show that the normalised spatio-temporal correlation of $h_q(\mathbf{q}_M(t), t)$ is:

$$\begin{aligned} \mathbb{E}[h_q(\mathbf{q}_M(t_1),t_1)h_q^*(\mathbf{q}_M(t_2),t_2)] &= \mathbb{E}[h(\mathbf{q}(t_1))h^*(\mathbf{q}(t_2))] \\ &= J_0\left(\frac{2\pi\|\Delta(\mathbf{q}_M(t_1),\mathbf{q}_M(t_2),t_1,t_2)\|_2}{\lambda_c}\right) \\ &\triangleq r\left(\mathbf{q}_M(t_1),\mathbf{q}_M(t_2),t_1,t_2\right). \end{aligned} \tag{8}$$

with

$$\begin{aligned} \Delta(\mathbf{q}_M(t_1),\mathbf{q}_M(t_2),t_1,t_2) &= \mathbf{R}^{-1}(\phi(t_2))\mathbf{q}_M(t_2) \\ &- \mathbf{R}^{-1}(\phi(t_1))\mathbf{q}_M(t_1) \\ &+ \mathbf{p}(t_2)-\mathbf{p}(t_1). \end{aligned} \tag{9}$$

It is worth noting that when the MR moves at a constant speed, the spatio-temporal correlation model described by (8) is equivalent to the spatio-temporal model presented in [8] for the case in which only a single antenna is used for transmission.

Now, we can define the coherence time mathematically as the time in which the channel observed by the antenna at a constant position $\mathbf{q}_M$ becomes decorrelated (i.e., the spatio-temporal correlation function becomes lower than a certain value η). So, mathematically this is defined as the smallest duration τ such that

$$r\left(\mathbf{q}_M,\mathbf{q}_M,t,t+\tau\right) < \eta. \tag{10}$$

Clearly, the coherence time at time instant nT is the smallest value τ that satisfies:

$$\|\Delta(\mathbf{q}_M,\mathbf{q}_M,nT,nT+\tau)\|_2 > z_\eta \tag{11}$$

where z_η is the smallest distance z that satisfies $J_0\left(\frac{2\pi z}{\lambda_c}\right)=\eta$. By observing (9) we note that the coherence time depends on the trajectory of the MR and hence is time dependent and also depends on η. So we will denote the coherence time as $\tau(\mathbf{q}_M(nT), nT, \eta)$.

As mentioned before, the duration of the UDP packet is αT and to ensure the proper reception of the packet we need to satisfy $\alpha T \leq \tau(\mathbf{q}_M(nT), nT, \eta)$ where η is selected according to the particular modulation scheme used.

B. Antenna position optimisation

To optimize the antenna's position $\mathbf{q}_M((n+1)T)$ at time instant $(n+\alpha)T$ the controller operates as follows. First it feeds the estimate of the channel observed during the reception of the current UDP packet (i.e., during $t \in [nT, (n+\alpha)T]$) into the channel predictor of order[5] one presented in [1]. We will assume that the duration of the UDP packet αT is inferior to the coherence time and so the channel estimated with the UDP's header is the same channel observed during the whole reception of the packet. Finally the controller determines the optimum antenna position that maximises the expected SNR during the reception of the next UDP packet by solving:

$$\begin{aligned} &maximize_u \qquad \mathbb{E}\left[|\tilde{h}_q(\mathbf{q}_M((n+1)T),(n+1)T)|^2\right] \\ &\text{s.t.} \\ &\mathbf{q}_M(t)=\rho\left[\cos\left(\omega(t)\right),\ \sin\left(\omega(t)\right)\right]^{\mathrm{T}}, \\ &\dot{\omega}(t)=u(t), \quad |u(t)|\leq U_{max}, \\ &\mathbf{q}_M(t)\in\mathcal{A}_M(\mathbf{q}_M(nT),t-(n+\alpha)T) \\ &\forall t\in[(n+\alpha)T,(n+1)T] \end{aligned} \tag{12}$$

where $\tilde{h}_q(\mathbf{q}_M((n+1)T),(n+1)T)$ is the channel predictor of memory order one introduced in [1], calculated at time instant nT, for $h_q(\mathbf{q}_M((n+1)T),(n+1)T)$ given the estimate of the channel $h_q(\mathbf{q}_M(nT), nT)$ and positions $\mathbf{q}_M(nT)$ as well as $\mathbf{p}(nT)$, $\phi(nT)$, $\mathbf{p}((n+1)T)$, $\phi((n+1)T)$. Using such a predictor the optimization target of (12) takes the form:

$$\begin{aligned} \mathbb{E}\left[|\tilde{h}_q(\mathbf{q}_M((n+1)T),(n+1)T)|^2\right] = 1+ \\ r^2\left(\mathbf{q}_M(nT),\mathbf{q}_M((n+1)T),nT,(n+1)T\right)\times \\ \left(|\hat{h}_q(\mathbf{q}_M(nT),nT)|^2-1\right), \end{aligned} \tag{13}$$

[5]We could use a predictor of a higher-order but we choose order one for simplicity purposes in this paper.

where $\hat{h}_q(\mathbf{q}_M(nT), nT)$ is an estimate for the channel $h_q(\mathbf{q}_M(nT), nT)$. Note that when evaluating the correlation function $r^2(\mathbf{q}_M(nT), \mathbf{q}_M((n+1)T), nT, (n+1)T)$ we use an estimate of the wavelength λ_c in (8) referred to as $\hat{\lambda}_c$.

Now, in order to avoid undesired oscillations of the antenna $\mathbf{q}_M$ we constrain the platform to turn in a single sense by adding $u(t) \geq 0$ or $u(t) \leq 0$ to (12). Note also that in practical systems rapid oscillations of the rotational platform, where the antenna is located, could have negative effects on the mechanical system. Hence we are interested in restricting the rotation to the minimum possible.

The solution of the problem (12) depends only on the final angular position of the antenna $\omega((n+1)T)$ and not on the particular form of $u(t)$. For simplicity, we restrict $u(t) = \omega_d^*/(\alpha T)$ for $t \in [(n+\alpha)T, (n+1)T]$ where ω_d^* is the optimum angular displacement. To solve (12) we create a grid over the range of allowed angular displacement and use a brute force search algorithm to find ω_d^*. Since the feasible range of angular displacement is small then this optimization method is quick enough.

IV. Simulations

In this section we present some simulation results to validate our proposed controller as a proof of concept and also to gain insight into its behaviour. We assume that the wavelength used is $\lambda_c =$14.02cm corresponding to a carrier frequency of 2.14GHz. Then we consider a MR with a revolving platform of radius $\rho = 10$cm controlled by a motor with a maximum rotational speed of[6] 200 RPM (revolutions per minute).

For simplicity we evaluate our antenna controller on a MR moving in a straight line with a uniform linear velocity and constant orientation $\phi(t) = 0$. The small-scale fading is simulated using Jakes' model.

In the first set of simulations we choose a transmission period of $T = 100$ms with a UDP packet duration of $\alpha T = 40$ms. In this case, due to both the constant linear speed and the constant orientation $\phi(t) = 0$ the coherence time is constant and $\tau(\mathbf{q}_M(nT), nT, 0.9) = 285.9$ms (defined with $\eta = 0.9$, see (10)-(11)).

We evaluate four different configurations: (i) MR's linear velocity of 5cm/s and initial angular position of $\mathbf{q}_M$ as $\omega(0) = 0$, no error estimation in the channel measurements used for the antenna controller and perfect knowledge of λ_c in the spatial correlation model (6); (ii) the same as (i) but with $\omega(0) = \pi$; (iii) the same as (ii) but with a linear velocity of 10cm/s; (iv) the same as (ii) but with noisy channel measurements (i.e., $\hat{h}_q(\mathbf{q}_M(nT), nT) = h_q(\mathbf{q}_M(nT), nT) + w_h(nT)$ with $w_h(nT) \sim \mathcal{CN}(0, \sigma_h^2)$ and $\sigma_h^2 = 0.1$) and with uncertainty in the wavelength used in (8) $\hat{\lambda}_c = \lambda_c(1 + w_\lambda(nT))$with $w_\lambda(nT) \sim \mathcal{CN}(0, \sigma_\lambda^2)$ and $\sigma_\lambda^2 = 0.1$). Also, as a reference scenario we consider the case in which $\mathbf{q}_M(t)$ is constant (i.e., no controller action) we will refer to this configuration as (0).

In Fig. 1 we observe the channel power (i.e., $\mathbb{E}[|h(\mathbf{q}(nT))|^2]$) whose behaviour can be divided into the transient state and the steady state (roughly after $n = 60$ in this particular case). Then, in Fig. 2 we plot the CDF of $|h(\mathbf{q}(100T))|$ (corresponding with the steady state of $\mathbb{E}[|h(\mathbf{q}(nT))|^2]$).

[6]Note that this is a relatively slow motor.

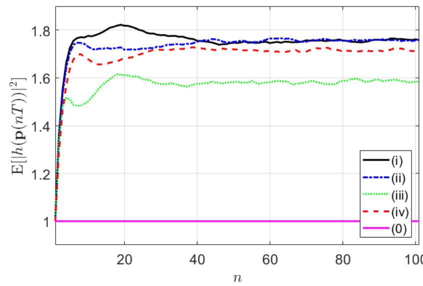

Fig. 1. Channel power for configurations (0)-(iv).

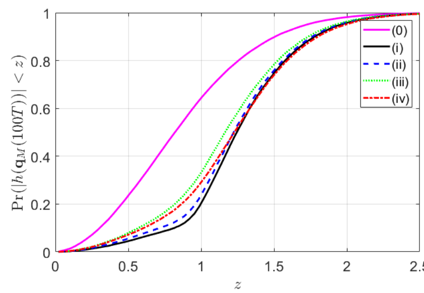

Fig. 2. CDF of the channel gain for configurations (0)-(iv).

First of all, when we compare configurations (0) and (i) we note that the antenna controller proposed can significantly improve the channel gain of the small scale fading (see Fig. 1) by reducing considerably the attenuation effect of the small scale fading (i.e., reducing the probability $\Pr(|h(\mathbf{q}(nT))| < 1)$), see Fig. 2.

Now, when comparing configurations (i) and (ii) we observe in Fig. 1 that the initial relative angular position of the antenna ($\omega(0)$) has only a small influence on the transient state but none in the steady state. On the other hand, when we compare configurations (ii) and (iii) we note that the velocity of the MR has an important effect in the performance of the controller. As the velocity of the MR increases the channel gain obtained is lowered, see Fig. 1, and the attenuation effect of the small scale fading is increased Fig. 2.

Configurations (i)-(iii) consider perfect knowledge of the channel gain and of the wavelength used in the controller to calculate the spatial correlation of the channel. Configuration (iv) shows us how the controller behaves in the presence of estimation error in the channel wavelength. This scenario corresponds to an SNR of 10dB in both estimations which is a significantly noisy case. Nevertheless when we compare (iv) with (ii) in Figs. 1-2 the channel gain and the attenuation probability are slightly worsen and the benefits are still significant in comparison to the configuration (0) where the position of the antenna remains static on the MR. Hence this controller presents a certain degree of robustness against estimation errors on the parameters required to operate.

Now, in Fig. 3 we present the behaviour of the channel gain for different UDP packets durations (i.e., αT), a constant transmission period of $T = 100$ms and the same estimation error conditions of the configuration (iv) mentioned above. As the duration the UDP packet increases the time that the antenna has to move (i.e., $(1-\alpha)T$) decreases and so the antenna reachability space $\mathcal{A}_M(\Pi_M, (1-\alpha)T)$ shrinks (see section II-A) and as a consequence the channel gain obtained also decreases. Note also that as α increases the duration of the transient state grows (see Fig. 3).

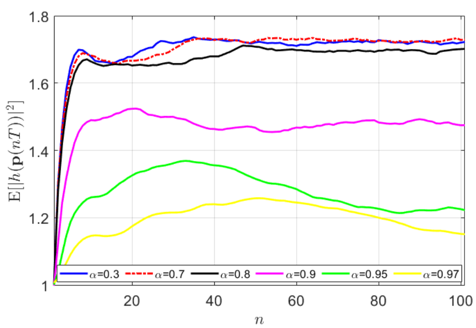

Fig. 3. Channel power for different UDP packet durations αT.

Then, in Fig. 4 we observe this time the behaviour of the channel gain for a constant UDP packet duration of $\alpha T = 40$ms and different transmission periods T. Although the antenna reachability space $\mathcal{A}_M(\Pi_M, (1-\alpha)T)$ whereas as T increases, the channel gain obtained decreases. This is because as T increases the maximum correlation that can be obtained between consecutive small-scale fading terms decreases (see (8)). Therefore, from Figs. 3 and 4 we note

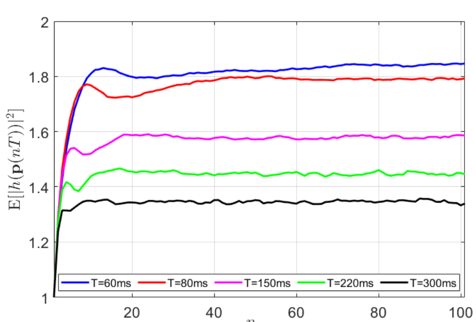

Fig. 4. Channel power for different transmission periods T.

that in order to obtain good performance from the controller we should select small values of both T and α.

V. Conclusions

In this paper we have proposed a new closed-loop antenna controller system for MRs which is capable of significantly improving the wireless communication channel without the necessity of altering the pre-determined trajectory of the MR or interfering with any of its tasks. Another important benefit of our system is that it does not require the introduction of any delay in the reception of the payload making our system suitable for applications in which low latency is required. Results show that this system can effectively compensate for the small-scale fading in a non-conventional way showing robustness against significant estimation errors in the parameters required by the system to operate. More work is required to better understand its capacity and limitations and so future research will analyse in more detail the impact of the MR trajectory on the overall performance of the system. Finally the limitations of our system due to the dynamics of the revolving platform will also be investigated in future work.

References

[1] D. Bonilla Licea, D. McLernon and M. Ghogho, "Mobile Robot Path Planners With Memory for Mobility Diversity Algorithms," in IEEE Transactions on Robotics, vol. 33, no. 2, pp. 419-431, Apr. 2017

[2] Jonathan Fink, Alejandro Ribeiro and Vijay Kumar, "Robust Control of Mobility and Communications in Autonomous Robot Teams", IEEE Access (Volume: 1), pp. 290 - 309, 2013.

[3] Arjun Muralidharan and Yasamin Mostofi, "Path Planning for a Connectivity Seeking Robot", Proceedings of the 2017 IEEE Globecom Workshops (GC Wkshps).

[4] Usman Ali, Hong Cai, Yasamin Mostofi and Yorai Wardi, "Motion and Communication Co-optimization with Path Planning and Online Channel Prediction", Proceedings of the 2016 American Control Conference (ACC), Boston, MA, USA.

[5] H. Jaleel, Y. Wardi and M. Egerstedt, "Minimizing mobility and communication energy in robotic networks: An optimal control approach", Proceedings of the 2014 American Control Conference (ACC).

[6] Magnus Lindhé and Karl Henrik Johansson, "Exploiting multipath fading with a mobile robot", The International Journal of Robotics Research Vol 32, Issue 12, 2013, pp. 1363–1380.

[7] J. M. Smith, M. P. Olivieri, A. Lackpour and N. Hinnerschitz, "RF-mobility gain: concept, measurement campaign , and explotation", IEEE Wireless Communications, vol. 16, no. 1, February 2009.

[8] Zoltan Safar and K. J. Ray Liu, "Space-time correlation of MIMO flat Rayleigh fading channels", Proceedings of the 2002 11th European Signal Processing Conference.

[9] D. Puccinelli and M. Haenggi, "Spatial Diversity Benefits by Means of Induced Fading", 3rd Annual IEEE Communications Society on Sensor and Ad Hoc Communications and Networks, 2006. SECON '06.

[10] S.M. Alamouti , "A simple transmit diversity technique for wireless communications", IEEE Journal on Selected Areas in Communications, Volume: 16 , Issue: 8 , Oct 1998.

[11] D. Bonilla Licea, M. Ghogho, D. McLernon and Syed Ali Raza Zaidi, "Mobility Diversity-Assisted Wireless Communication for Mobile Robots," in IEEE Transactions on Robotics, vol. 32, no. 1, pp. 214-229, Feb. 2016.

[12] A. Ghaffarkhah and Y. Mostofi, "Path planning for networked robotic surveillance," IEEE Transactions on Signal Procesing, vol. 60, no. 7, July 2012.

[13] Chia Ching Ooi and Christian Schindelhauer, "Minimal Energy Path Planning for Wireless Robots", Mobile Networks and Applications (2009) 14: 309.

[14] Usman Ali, Yuan Yan, Yasamin Mostofi and Yorai Wardi, "An Optimal Control Approach for Communication and Motion Co-optimization in Realistic Fading Environments", Proceedings of the 2015 American Control Conference (ACC).

[15] Yuan Yan and Yasamin Mostofi, "To Go or Not to Go: On Energy-aware and Communication-aware Robotic Operation", IEEE Transactions on Control of Network Systems (Volume: 1 , Issue: 3 , Sept. 2014)

[16] Sergio Caccamo, Ramviyas Parasuraman, Luigi Freda, Mario Gianni and Petter Ögren, "RCAMP: A resilient communication-aware motion planner for mobile robots with autonomous repair of wireless connectivity", Proceedings of the 2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS).

[17] Mehrzad Malmirchegini and Yasamin Mostofi, "On the Spatial Predictability of Communication Channels", IEEE Transactions on Wireless Communications (Volume: 11 , Issue: 3 , March 2012)

[18] W.C. Jakes, *Microwave Mobile Communications*, Wiley. IEEE Press, New York, 1994.

[19] M. K. Simon; M. Alouini, *Digital Communication Over Fading Channels*, Wiley. IEEE Press, 2005.