Predicting Wireless Channels for Ultra-Reliable Low-Latency Communications

Vasuki Narasimha Swamy*, Paul Rigge*, Gireeja Ranade*†, Borivoje Nikolić*, Anant Sahai*

*University of California, Berkeley, CA, USA, †Microsoft Research, Redmond, WA, USA

***Abstract*—Ultra-reliable, low-latency wireless communication is essential to enable critical and interactive applications. The cooperative communication schemes for such ultra-reliable communication must harvest multi-user diversity to achieve their specifications. The underlying low-latency space-time codes for a large number of users (> 10) place burdens on practical implementations due to the large number of simultaneous relays they must use. To address this, we propose an adaptive relay selection technique that selects a small set of good relays, instead of using every available radio to relay. Using our simple relay-selection schemes, we can support a network with 30 nodes requiring system failure probability under 10^{-9} and 2ms latency with only 3 simultaneously active relays per message. In contrast, in the absence of adaptive relay selection, we must rely on 13 relays to achieve the same reliability.**

To arrive at such relay selection schemes, we revisit the fading dynamics of wireless channels in the context of ultra-high reliability. Contrary to what has been claimed in the literature, we find that standard Rayleigh fading processes are *not bandlimited*. However, these fading processes are fairly predictable on the short time scales of the regime of interest.

***Keywords*—Fading process, low-latency, high-reliability wireless, industrial control, Internet-of-Things, machine learning**

I. Introduction

Some of the most exciting and challenging IoT applications (e.g. vehicle platooning, exoskeletons for healthcare, and smart factories [1]) demand ultra-reliable, low-latency communication (URLLC). In these applications, networks ranging in size from 10 to 100 nodes require short packets (10 to 50 bytes) to be exchanged with latencies on the order of 1ms and system error rates under 10^{-9}. It is understood that getting wireless errors below 10^{-5} to 10^{-6} is challenging [2]–[4]. Time-diversity based schemes violate latency requirements and frequency-diversity based schemes are grossly inefficient. It has been shown that cooperative communication based relaying schemes are a good fit for these applications because multi-user diversity can provide ultra-high reliability while meeting the latency requirements at moderate SNR [5], [6].

A. The need for relay selection

Since it takes too long to take turns, employing *simultaneous* relaying with a distributed space-time-code (DSTC) is essential [7]. However, if we non-adaptively restrict the number of relays that may simultaneously transmit, then the minimum SNR required to meet the reliability demand grows tremendously – restricting the maximum number of relays to 5 increases the operating SNR by 15dB (Fig. 4 in [8]). To have a moderate nominal SNR, we need 13 or more simultaneous relays for moderate network sizes of > 20. Employing simultaneous relaying of 13 or more nodes is bad for the following reasonings:

(i) Not all nodes that participate in relaying have good channels to the destination. The energy spent on these links is wasteful and increases interference to other nearby networks.

(ii) To account for inaccuracies in local oscillators, cooperative communication requires implementations to dedicate significant resources to time and frequency synchronization and this scales with the number of simultaneous transmitters [9].

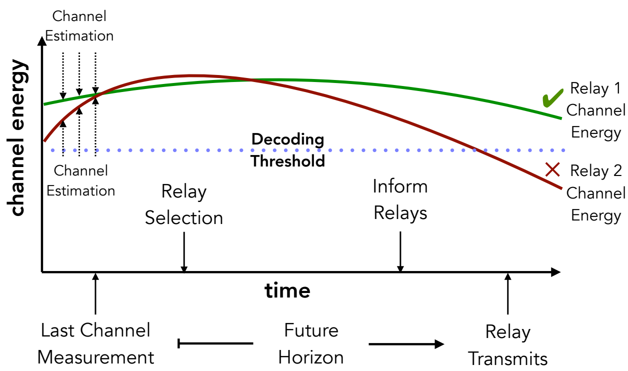

Fig. 1: After estimating channels, relays are selected and informed of their selection. During the time between channel estimation and the relays transmitting, the channels may change.

B. The need to revisit channel dynamics

One way to address the issue of having a large number of relays simultaneously transmitting is by selecting the relays that are good – those that will have a high SNR channel to the destination(s) during the relaying phase. Relay selection schemes have been extensively studied, but these schemes traditionally assume that the channels remain precisely the same from the last channel measurement to when they actually relay. Most studies focus on the decoding error at the receiver based on current channel coefficients [10]. Let's consider using these relay selection schemes without taking channel dynamics into account. If we assume that a channel might change significantly in a millisecond with probability 10%, then to achieve a reliability of 10^{-9}, we will need to choose *at least* 9 relays to be robust to these potential channel changes. This is an improvement over the 13 relays required if they are chosen blindly, but it is still a large number of nodes to have simultaneously transmitting. However, if fading channel dynamics are stable enough to predict channel quality more reliably (say an error rate of at most 10^{-3}), then we could rely on fewer relays.

To facilitate such predictions, we must solve a few important challenges. We only have potential relay's channel coefficient measurements for a certain period of time. Based on these channel coefficient measurements, we decide which nodes(s) to nominate as relays and disseminate that information. The node actually relays at a *future* time. In the time between the last channel coefficient measurement of the relay and actual relaying, the channel may change (potentially adversely) as illustrated in Fig. 1. But how do wireless channels change and how fast? Can channels be reliably predicted based on past channel realizations? If so, for what future horizons and at what reliability? To answer these questions we need to understand how wireless channels fundamentally change.

To predict channel quality reliably, we need to to revisit some well-established concepts:
(i) Coherence time is defined in the literature as the duration over which a wireless channel does not change significantly [11]. Is this time an average duration or a tail bound? What does coherence time look like as a random process?
(ii) Channel fading process is traditionally modeled as a bandlimited process [12]. However, our analysis and simulations of channel fading dynamics show that this is not the case for Rayleigh-type channels.

The main contributions of this paper are:

1) An analysis of wireless channel dynamics to provide evidence that fading processes are not bandlimited.
2) A redefinition of coherence time as the time for which a channel is predictable to a required fidelity.
3) An analysis of the relay-selection error based on channel dynamics.
4) A simple relay-selection scheme that can support a network with 30 nodes requiring system failure probability under 10^{-9} and 2ms latency with at most 3 simultaneously active relay nodes per message as opposed to needing > 10 simultaneously active relays [8].

II. Channel Models

We consider a Rayleigh-fading model for wireless channel between a transmitter and receiver pair. Rayleigh-faded channels have traditionally been modeled as coming from sum-of-sinusoides like in Jakes's model [13]. We revisit the dynamics of Rayleigh faded channels and challenge the concept that the channel fading dynamics are fundamentally bandlimited if the motions have bounded speed. We consider only the effects of multipath as we focus on the variations at small timescales as is traditional.

Consider a two-dimensional room with n static scatterers distributed uniformly at random. Let there be a static single-antenna transmitter in the middle of the room and a single-antenna mobile receiver moving at a constant speed v in some random direction inside the room. Let the transmitter be transmitting a tone at frequency f_c (wavelength λ_c). The channel coefficient between the transmitter and the receiver at any time t is given by

$$h(t) = \frac{1}{\sqrt{n}} \sum_{i=1}^{n} \exp\left(j \frac{2\pi (d_i^{(\text{Rx})}(t) + d_i^{(\text{Tx})})}{\lambda_c} \right) \quad (1)$$

where, $d_i^{(\text{Rx})}(t)$ is the distance of the scatterer i from the receiver at time t and $d_i^{(\text{Tx})}$ is the distance of the scatter i from the transmitter (both the transmitter and scatter are assumed to not be moving for simplicity). Eq. (1) follows from [14].

A. Channel variation as a Gaussian process

We want to understand how channels between a pair of antennas vary as one (or both) antennas move while the environment remains largely stationary. The model depicted by Eq. (1) captures the small-scale variations that we are interested in, where the nodes are moving at a reasonable speed but for small amounts of time (in ms). The knowledge of channel variations at millisecond scales can then help us build relay selectors that can pick the right relay(s) for each message stream. The channel coefficient at any point in time is marginally distributed as a complex normal (as the CLT suggests for the expression in Eq. (1)), and the channel coefficient process can be modeled as a Gaussian process. The parameters that we need to define the Gaussian process are the means and the covariance functions which depend on the distance between the positions of the receiver. We assume that the velocity $\vec{v}$ of the receiver is constant over the time durations that we are interested in such that the position of the receiver at time t is given by

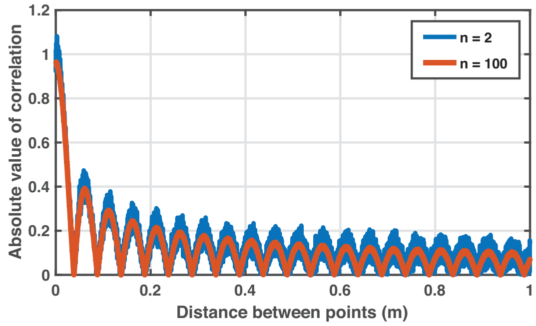

Fig. 2: Simulated absolute value of the cross-covariance of the fading process for $f_c = 3$GHz. The curves are exactly as predicted by Eq. 5 even for a small number of scatterers $n = 2$.

$$\vec{s}(t) = \vec{s_0} + \vec{v}t = (x_0 + vt\cos\phi, y_0 + vt\sin\phi) \quad (2)$$

where $\vec{s_0} = (x_0, y_0)$ is the initial position of the receiver at time $t = 0$ (uniformly distributed in the room), ϕ is the angle of motion of the receiver with respect to the x-axis (uniformly distributed over $[0, 2\pi)$). Let the position of scatterer i be given by $\vec{s_i} = (x_i, y_i)$. The distance of the receiver from scatterer i at time t is given by

$$\begin{aligned} d_i^{(\text{Rx})}(t) &= \|\vec{s}(t) - \vec{s_i}\| \\ &= \sqrt{(x_0 + vt\cos\phi - x_i)^2 + (y_0 + vt\sin\phi - y_i)^2} \\ &= \sqrt{d_i^{(\text{Rx})}(0)^2 + (vt)^2 + 2vtd_i^{(\text{Rx})}(0)(\cos\theta_i\cos\phi + \sin\theta_i\sin\phi)} \\ &= \sqrt{d_i^{(\text{Rx})}(0)^2 + (vt)^2 + 2vtd_i^{(\text{Rx})}(0)\cos(\theta_i - \phi)} \quad (3) \end{aligned}$$

where $d_i^{(\text{Rx})}(0)$ is the distance of the receiver from the scatterer i at time $t = 0$ and θ_i is the angle made by the line joining the scatterer and the receiver at time $t = 0$ which is independent of ϕ. We are interested in the cross-covariance $k(v, t)$ of the in-phase and quadrature components as a function of speed v and time t. To calculate that, we look at $\tilde{k}(v, t) = \mathbb{E}[h(t)h^*(0)] = 2k(v, t)$. We have,

$$\begin{aligned} &\tilde{k}(v, t) = \mathbb{E}[h(t)h^*(0)] \\ &= \frac{1}{n}\mathbb{E}\left[\sum_{i=1}^{n} \exp\left(j\frac{2\pi}{\lambda_c}\left(d_i^{(\text{Rx})}(t) - d_i^{(\text{Rx})}(0) \right) \right) \right. \\ &\left. + \sum_{i \neq j} \exp\left(j\frac{2\pi}{\lambda_c}\left(d_i^{(\text{Rx})}(t) - d_j^{(\text{Rx})}(0) + d_i^{(\text{Tx})} - d_j^{(\text{Tx})} \right) \right) \right] \end{aligned}$$

As $d_i^{(\mathrm{Rx})}(t)$ and $d_j^{(\mathrm{Rx})}(0)$ are independent for $i \neq j$ and the scatterers are distributed uniformly across the room, the expectation of the second term in the above equation is 0. Hence,

$$\tilde{k}(v,t) = \mathbb{E}\left[\exp\left(j\frac{2\pi}{\lambda_c}\left(d_i^{(\mathrm{Rx})}(t) - d_i^{(\mathrm{Rx})}(0)\right)\right)\right]. \quad (4)$$

Substituting, Eq. (3) in Eq. (4), for small movements ($\frac{vt}{d_i} \approx 0$), the covariance function is given by

$$\tilde{k}(v,t) = J_0\left(\frac{2\pi}{\lambda_c}vt\right), \quad (5)$$

where $J_0(\cdot)$ is the Bessel function of the first kind as also derived in [12]. Fig. 2 shows the simulated absolute value of the expected cross-covariance of the fading process as a function of distance and this exactly matches Eq. (5).

B. Bandwidth of fading processes

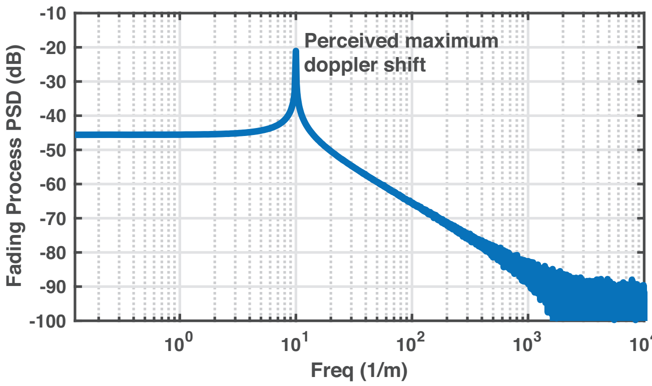

Fig. 3: One-sided PSD of the fading process for $f_c = 3$GHz

The spectral density of the covariance function of the fading process has indeed been looked at in studies like [12], [13], [15]. However, they make an essential assumption: that the power spectrum is bowl shaped and the contribution of frequencies higher than the perceived maximum frequency is zero – essentially, the fading process is bandlimited. The unilateral Laplace transform of the Bessel function ($\mathcal{L}(J_0(x)) = 1/\sqrt{1+s^2}$) has poles on the imaginary axis. Therefore, the Fourier transform gets tricky – how do we deal with these poles? Studies so far (such as [12], [13], [15]) seem to have elected to restrict the Fourier transform of the Bessel function until the maximum Doppler shift (i.e., v/λ_c), possibly to address these poles. However, our simulations showed that the fading process has energy beyond the perceived maximum doppler shift. This surprising discovery was also supported by looking numerically directly at the Bessel function[1]. This is especially relevant given that we are interested in rare events and predictability.

Figure. 3 plots the one-sided power spectral density of the fading process, for center frequency $f_c = 3$GHz (obtained through simulations). We do see the bowl shape that is traditionally expected until spatial frequency of 10/m (corresponding to the maximum Doppler frequency) but it clearly doesn't die down to 0 immediately beyond the maximum Doppler frequency, instead decaying at the rate of 20dB per decade.

[1]We have uploaded a Jupyter notebook showing that the Bessel function is not bandlimited at `https://github.com/grebe/besselpsd`. This interactive notebook lets you vary different parameters.

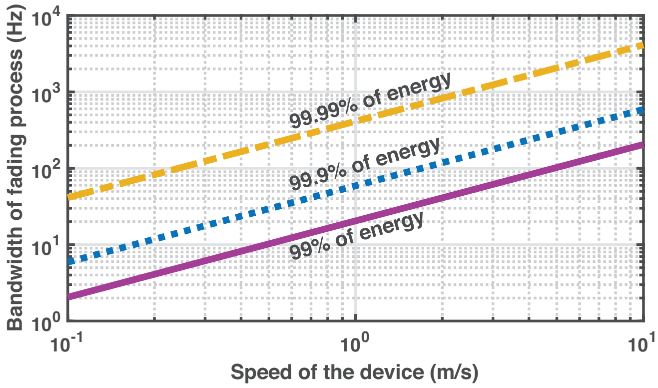

Fig. 4: Bandwidth around the center frequency which captures 99%, 99.9% and 99.99% of the energy of the fading process as a function of node speed

Traditionally, the bandwidth of a process has been characterized through the amount of energy in it. Fig. 4 plots the bandwidth that contains 99%, 99.9% and 99.99% of the energy for various node speeds for center frequency $f_c = 3$GHz. We see the expected linear scaling with speed but we also see the increase in bandwidth with increasing energy content. We can infer from this figure that we need a high sampling rate to get high prediction accuracy for the process. Because we are sampling a non-bandlimited process[2], the amount of energy captured in a given bandwidth determines the fidelity of prediction.

III. Channel Quality & Relay Selection

So far we have explored channel dynamics to understand how they behave at a finer detail. In this section, we describe how to use the proposed channel dynamics model to predict channel coefficients. We use this to redefine coherence time and to arrive at a lower bound for the error in selecting the best relay. Then, we will give a simple scheme for relay selection.

A. Channel Prediction

We want to pick a small set of relays instead of having a large number of nodes simultaneously transmit. What is the best prediction for the channel coefficient at a future time given the knowledge of past channel coefficients? We assume the following:

- The source node picks relays and has knowledge of the past channel coefficients between the source-relay and relay-destination.
- The source knows the speed v at which it is moving, therefore it knows how far it will travel in a given time.
- The node also has knowledge of channel statistics, e.g. the covariance function of the fading process.

Consider the channel between the source and a relay. The source has knowledge of past channel coefficients $\vec{h}$ =

[2]The question of whether multipath fading is bandlimited also has information-theoretic consequences. Non-bandlimited fading processes were studied in [16] and the capacity was found to scale as $\log\log\mathrm{SNR}$ (as opposed to $\log\mathrm{SNR}$ for bandlimited fading processes), showing a fundamental difference between non-bandlimited and band-limited fading.

$[h_1 \quad h_2 \quad \dots \quad h_m]^T$ from times $\vec{t} = [t_1 \quad t_2 \quad \dots \quad t_m]^T$. We want to find the distribution of h_{m+1} at time t_{m+1} conditioned on $\vec{t}$ and $\vec{h}$. We assume that the channel coefficient variation is a Gaussian process, and use simple linear estimation. We assume that $\{\vec{h}, h_{m+1}\}$ form a multivariate normal and the distribution of h_{m+1} conditioned on $\vec{h}$ is a complex normal distribution. Let

$$\mathbf{K} = \begin{bmatrix} k(v, t_1 - t_1) & k(v, t_2 - t_1) & \dots & k(v, t_m - t_1) \\ k(v, t_2 - t_1) & k(v, t_2 - t_2) & \dots & k(v, t_m - t_2) \\ \vdots & \vdots & \ddots & \vdots \\ k(v, t_m - t_1) & k(v, t_m - t_2) & \dots & k(v, t_m - t_m) \end{bmatrix}$$

be the covariance matrix corresponding to the times of observations so far. Let

$$\mathbf{K}_* = [k(v, t_{m+1} - t_1) \quad \dots \quad k(v, t_{m+1} - t_m)]$$

be the covariance matrix corresponding to the future time of interest and the times of observations so far. Also, let $\mathbf{K}_{**} = [k(v, t_{m+1} - t_{m+1})]$. Let $\vec{h}_I = \text{Re}\{\vec{h}\}$ be the vector of the in-phase components of $\vec{h}$ and $\vec{h}_Q = \text{Im}\{\vec{h}\}$ be the vector of the quadrature components of $\vec{h}$. Then, the mean of the distribution of the in-phase μ_I and the quadrature component μ_Q of h_{m+1} conditioned on $\vec{t}$ and $\vec{h}$ is given by

$$\mu_I = \mathbf{K}_* \mathbf{K}^{-1} \vec{h}_I, \quad \mu_Q = \mathbf{K}_* \mathbf{K}^{-1} \vec{h}_Q. \tag{6}$$

The variance of both the in-phase and quadrature components is given by

$$\sigma^2 = \mathbf{K}_{**} - \mathbf{K}_* \mathbf{K}^{-1} {\mathbf{K}_*}^T. \tag{7}$$

The quality of a channel is captured by the energy ($|h|^2$) in it. The distribution of the energy $|h_{m+1}|^2$ is given by

$$|h_{m+1}|^2 \sim \text{Rice}(\nu, \sigma) \tag{8}$$

where $\text{Rice}(\nu, \sigma)$ is the Rician distribution with parameters ν and σ given by $\nu = \sqrt{\mu_I^2 + \mu_Q^2}$, and σ is given by Eq. (7).

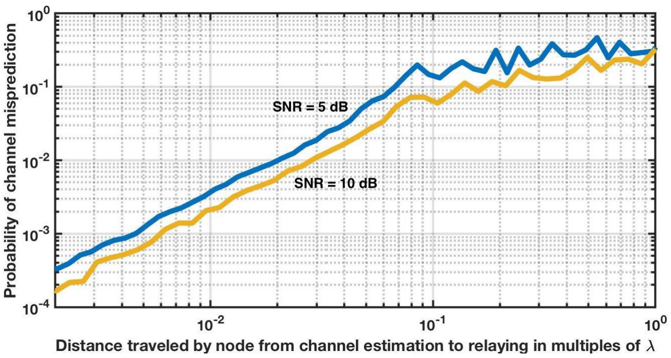

Fig. 5: The probability of channel quality misprediction as a function of how far the node has moved (at 10m/s) since the last channel measurement. This figure was obtained for a sampling frequency of 1kHz, and nominal SNRs 5 and 10dB.

B. Redefining Coherence Time/Distance

Coherence time or distance has traditionally been thought of as the time or distance over which the channel stays constant, which is a good rule of thumb for cellular systems that focus on average performance. However, URLLC requires guarantees on worst-case performance which challenges the traditional notion of coherence time/distance. To this end, **we propose a more nuanced notion of coherence time or distance: the time or distance over which a channel is predictable with a given reliability.**

Fig. 5 essentially shows the distribution of coherence distance (in units of wavelengths) for a single channel. This was obtained by considering error in predicting a channel (distributed as Eq. (8)) to be good or bad when operating at nominal SNRs of 5 and 10dB. We see that the prediction is incorrect about 0.2% of the time even when the node has moved only $\frac{1}{100}^{\text{th}}$ of the wavelength. In fact, the rule-of-thumb is that for every order of magnitude in distance, the probability of error goes up by about 1.5 orders. It plateaus around the unconditional outage probability which is what one would expect if a node travels sufficiently far – to have little channel correlation from where it began. We observe that if nodes are moving at 10m/s and the future horizon is 1ms (corresponding to 10mm distance), then for center frequency of 3GHz, a channel would be incorrectly perceived about 0.1% (or 10^{-3}) of the time. This suggests that one would need to nominate 3 relays to have enough redundancy to account for the channel prediction error to achieve an overall error probability of 10^{-9}.

C. Relay Quality

For a relay to be a good relay, two different channels (source-relay h_{sr} and destination-relay h_{dr} channels) have to be good at the future time when the node relays. We define the badness b_r of a relay r as the probability that either $|h|^2_{sr}$ or $|h|^2_{dr}$ is not a good channel. Since $|h|^2_{sr} \sim \text{Rice}(\nu_{sr}, \sigma_{sr})$, the probability that the energy is less than the threshold γ is $F_{sr} = 1 - Q_1\left(\frac{\nu_{sr}}{\sigma_{sr}}, \frac{\gamma}{\sigma_{sr}}\right)$ where Q_1 is the Marcum Q-function [17]. The same is true for h_{dr}. Therefore, the badness of a relay r is given by

$$b_r = P(\min\left(|h|^2_{sr}, |h|^2_{dr}\right) < \gamma) = F_{sr} + F_{dr} - F_{sr} \cdot F_{dr}. \tag{9}$$

Given a choice of k independent relays (numbered 1 to k), the probability that the best relay is not good enough is lower bounded by p_{lower}, which is given by,

$$p_{lower} = \min\left(b_1, b_2, \dots, b_k\right). \tag{10}$$

The main variables that determine the value of p_{lower} as defined in Eq. (10) are, 1) the sampling frequency, 2) the future horizon, 3) the number of potential relays to choose from (k), and 4) the nominal SNR and the rate of transmission (they together determine the threshold γ). Fig. 6 shows the effect of sampling frequency and future horizon. Consider the solid set of curves for $k = 9$. We see that prediction error for nearer future horizons (under 3ms) for sampling frequency of 1kHz – which is about the bandwidth containing 99.99% fading process energy for nodes moving at a speed of at most 10m/s, is excellent ($< 10^{-4}$). This suggests that nominating at most 2 relays would be sufficient to achieve reliability of 10^{-9}. As the future horizon increases, the prediction error quickly degrades to the unconditional outage probability, which is the error probability if a random relay is picked without any prior knowledge. We also see that the performance when we sample at lower frequencies (400Hz or lower) is bad and cannot be used in practice. Similar findings hold true for $k = 4$ nodes.

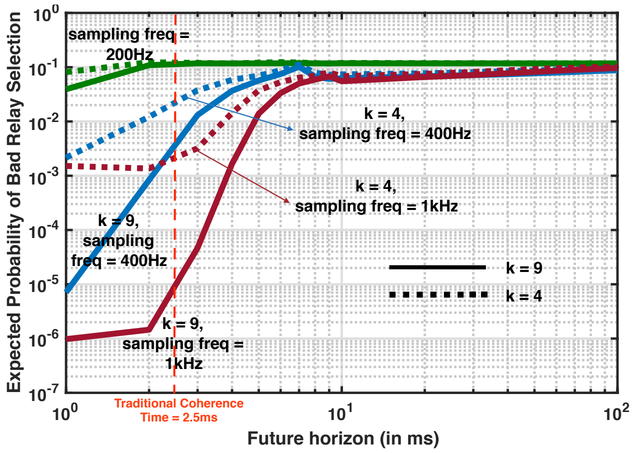

Fig. 6: Probability of best relay not being good enough for varying sampling frequency and future horizons. The model order is 3, the number of relays to choose from is $k = 9$ (solid curves) and $k = 4$ (dotted curves), nodes are moving in a random direction at speed 10m/s, nominal SNR is 5dB and the center frequency is $f_c = 3$GHz. The traditional coherence time for a radio moving at these parameters is 2.5ms (corresponding to moving $\lambda/4$ at 10m/s) which is marked on the plot.

D. Practical relay selection scheme

We have reformulated the relay-selection problem with emphasis on detailed channel dynamics knowledge. Based on the above findings, we built a simple local relay-selection scheme. We use channel knowledge from only a few recent samples to predict the channel quality and pick the best relay. We use a simple polynomial interpolator to fit a low-degree (at most 2) local polynomial on the past 4 channel coefficients to predict the future channel coefficient and therefore the energy. We use traditionally scoring metrics such as the relay with the maximum harmonic mean of source-relay and destination-relay channel energies or the relay with the maximum min-energy to select the best relay [10]. The results are equivalent.

We compared this scheme with schemes which did not consider any channel dynamics [10]. We used a sampling frequency of 1kHz and future horizon of 1ms for all the schemes. While non-dynamic relay-selection schemes have an error rate (i.e., the predicted best relay is bad) of 1%, our scheme has an error rate of only 0.1% – a 10x improvement over non-dynamic schemes which is consistent with the results found in Sec. III-B. This low error probability essentially suggests that we only need to nominate 3 relays, not greater than 10 as was originally needed. Indeed, when applied to the Occupy-CoW protocol from [7] at 5dB nominal SNR using 20MHz of bandwidth around 3GHz, this shows that it is possible to have 30 nodes (moving less than 10m/s) communicating 20byte messages to each other every 2ms with system probability of error less than 10^{-9} overall if we adaptively nominate the best predicted 3 relays per link.

IV. Conclusions

Adaptive relay selection is essential for enabling URLLC. To select good relays, we need to consider wireless channel dynamics and not assume that channels remain static upto the traditionally defined coherence time. We show that wireless fading processes are not bandlimited. We use the non-bandlimited fading process model to redefine coherence time and distance as the horizon for which a channel is predictable with a given fidelity. We formulated a framework for relay-selection based on modeling the channel dynamics as a Gaussian process and see that the error in selecting the best relay crucially depends on sampling frequency and future horizon. Our simple, practical, prediction-based relay selection scheme is 10x better than schemes that do not try to predict and just trust the traditional perspective on coherence time.

Acknowledgements

Thanks to Venkat Anantharam and Meryem Simsek for useful discussions. We also thank BWRC students, staff, faculty and industrial sponsors, NSF grants AST-1444078, CNS-1321155, and ECCS-1343398 and Microsoft for a Microsoft Research Dissertation Grant.

References

[1] G. Fettweis, "The Tactile Internet: Applications and Challenges," *Vehicular Technology Magazine, IEEE*, vol. 9, no. 1, pp. 64–70, March 2014.

[2] C.-P. Li *et al.*, "5G ultra-reliable and low-latency systems design," in *Networks and Communications (EuCNC), 2017 European Conference on*. IEEE, 2017, pp. 1–5.

[3] G. Durisi *et al.*, "Towards massive, ultra-reliable, and low-latency wireless: The art of sending short packets," *CoRR*, vol. abs/1504.06526, 2015. [Online]. Available: http://arxiv.org/abs/1504.06526

[4] B. Holfeld *et al.*, "Wireless communication for factory automation: An opportunity for LTE and 5G systems," *IEEE Communications Magazine*, vol. 54, no. 6, pp. 36–43, 2016.

[5] V. Narasimha Swamy *et al.*, "Cooperative communication for high-reliability low-latency wireless control," in *2015 IEEE International Conference on Communications*, June 2015, pp. 4380–4386.

[6] ——, "Network coding for high-reliability low-latency wireless control," in *2016 IEEE Wireless Communications and Networking Conference Workshop on The Tactile Internet*, Doha, Qatar, Apr. 2016.

[7] V. Narasimha Swamy *et al.*, "Real-time cooperative communication for automation over wireless," *IEEE Transactions on Wireless Communications*, vol. 16, no. 11, pp. 7168–7183, Nov 2017.

[8] ——, "Robustness of cooperative communication schemes to channel models," in *2016 IEEE International Symposium on Information Theory (ISIT)*. IEEE, 2016, pp. 2194–2198.

[9] Q. Huang *et al.*, "Practical timing and frequency synchronization for OFDM-based cooperative systems," *IEEE Transactions on Signal Processing*, vol. 58, no. 7, pp. 3706–3716, 2010.

[10] Y. Jing *et al.*, "Single and multiple relay selection schemes and their achievable diversity orders," *IEEE Transactions on Wireless Communications*, vol. 8, no. 3, pp. 1414–1423, 2009.

[11] T. S. Rappaport *et al.*, *Wireless communications: principles and practice*. Prentice Hall PTR New Jersey, 1996, vol. 2.

[12] M. J. Gans, "A power-spectral theory of propagation in the mobile-radio environment," *IEEE Transactions on Vehicular Technology*, vol. 21, no. 1, pp. 27–38, 1972.

[13] W. C. Jakes *et al.*, *Microwave mobile communications*. Wiley-IEEE Press, 1994.

[14] M. F. Pop *et al.*, "Limitations of sum-of-sinusoids fading channel simulators," *IEEE Transactions on communications*, vol. 49, no. 4, pp. 699–708, 2001.

[15] K. E. Baddour *et al.*, "Autoregressive modeling for fading channel simulation," *IEEE Transactions on Wireless Communications*, vol. 4, no. 4, pp. 1650–1662, 2005.

[16] A. Lapidoth, "On the asymptotic capacity of stationary Gaussian fading channels," *IEEE Transactions on Information Theory*, vol. 51, no. 2, pp. 437–446, 2005.

[17] "Marcum Q-function," http://mathworld.wolfram.com/MarcumQ-Function.html.