Information transmission bounds in mobile communication networks

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Abstract— Networks of autonomous agents are becoming ubiquitous, motivating the challenging task of developing control policies for communication across these networks. The aim is usually to maximize the data transmission rate, or to reliably transfer a minimum amount of data subject to network constraints. For a stationary transmitter-receiver pair under an average transmit power constraint, the total amount of data that can be transmitted is unbounded as transmission time tends to infinity. We show that, in contrast, if the transmitter is moving at a constant speed, then the maximum amount of data that can be transmitted is bounded. This bound is of particular relevance to networks of aerial vehicles, where distances may quickly grow large and channel gain is dominated by path loss dynamics.

I. Extended Abstract

The Shannon capacity is a communication-theoretic limit on the achievable data rate for reliable transmission across a noisy channel. The corresponding upper bound on the total transmittable data over time T is

$$D_T := B \int_0^T \log_2\left(1 + \mathrm{SNR}(t)\right) \mathrm{d}t \quad \text{bits}, \tag{1}$$

where B is the bandwidth and $\mathrm{SNR}(t)$ is the time-varying signal-to-noise ratio at the receiver.

Consider transmission over a wireless channel where the receiving node is positioned at the origin and a mobile transmitter with initial position x_0 is moving at a constant speed v away from the receiver. At time t the transmitter's distance from the receiver is $x(t) = x_0 + vt$. Neglecting fast-fading dynamics, we assume the channel gain is dominated by a line-of-sight (LoS) component, typical of aerial inter-UAV channels. The SNR at the receiver may be written as

$$\mathrm{SNR}(t) := \frac{PG}{\sigma^2}\left(\frac{d_0}{x(t)}\right)^{\alpha}, \tag{2}$$

where σ^2 is the noise power at the receiver, $\alpha > 1$ is the path loss exponent (typically close to 2 for LoS applications), d_0 is the reference distance satisfying $d_0 \leq x(t)$, $\forall t \geq 0$, P is the transmission power, assumed to remain constant throughout transmission, and G is a unitless antenna parameter representing gain and path loss at the reference distance d_0.

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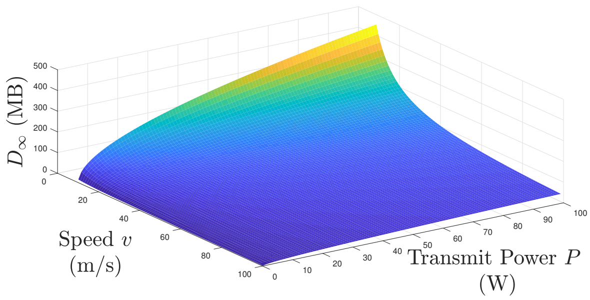

Fig. 1: Maximum transmittable data D_∞ as a function of transmitter speed v and power P, for parameters $\sigma^2 = 10^{-8}$ W, $d_0 = 1$ m, $B = 10^5$ Hz and $G = 1$.

If the mobile transmitter starts arbitrarily close to the stationary receiver, at position $x_0 = d_0$, then an upper bound on the maximum achievable data transfer is

$$D_\infty := \lim_{x_T \to \infty} \frac{1}{v} \int_{d_0}^{x_T} \log_2\left(1 + \frac{PG}{\sigma^2}\left(\frac{d_0}{x}\right)^{\alpha}\right) \mathrm{d}x, \tag{3}$$

which differs from (1) in that the variable of integration has been switched from t to $x = x_0 + vt$. Under the assumption that the transmitted SNR $S := PG\sigma^{-2} > 1$, which is reasonable in practice, it can be shown that

$$D_\infty = \frac{B}{\ln(2)v}\left(\alpha \sqrt[\alpha]{S} d_0 \left\{\frac{\pi}{2\alpha}\csc\left(\frac{\pi}{\alpha}\right) + \frac{1}{2}\right\} + \alpha d_0 \left\{\sum_{n=1}^{\infty}\left(\frac{(-1)^{n+1}}{S^n(\alpha n + 1)}\right) - 1\right\} - d_0 \ln(1+S)\right), \tag{4}$$

where the infinite sum is bounded and may be evaluated explicitly for certain values of α. D_∞ may be used for computing a feedback policy, as a function of the control variables (P, v), for transmitting a given amount of data.

Consider a low-altitude UAV that must offload M bits to a ground station (GS) from which it it is departing. The maximum data transfer is upper bounded by D_∞, shown in Figure 1. The set of admissible control variables is $\{(P, v) \mid D_\infty = M\}$, from which (P, v) may then be chosen to achieve further control objectives, such as energy efficiency [1]. Furthermore, many transmitters only operate at a single, or finite set of power levels, in which case v may be found as an explicit function of (P, M). Importantly, when P is not a control variable, constant speed flight is often the most energy efficient.

References

[1] O. J. Faqir, E. C. Kerrigan, and D. Gündüz, “Joint optimization of transmission and propulsion in aerial communication networks,” arXiv preprint arXiv:1710.01529, 2017.