Utilization of Unidirectional Links through Cooperative ACKs

September 24, 2010

Introduction

- Wireless networks are inherently asymmetric.

- Protocols so far have been avoiding unidirectional links (because of lack of ACKs which are necessary for ARQ).

- Lately, there is much effort dedicated to exploiting unidirectional links, as well as developing alternative ARQ schemes.

- We are interested to study what improvement can we expect by utilizing unidirectional links with alternative ARQ schemes on dynamic network topologies.

System Model

We examine and compare two communication schemes in a multi-hop wireless network:

- first, a scheme (denoted b) that uses bidirectional links only,
- and second, a scheme (denoted u) that also uses unidirectional links.

The underlying network can either be canonical (e.g. square lattice) or random (e.g. Poisson).

All devices transmit with the same power.

System Model

The devices use ALOHA as the medium access control (MAC) protocol. The access probabilities are p_{data} and p_{ACK} for the common slot and the mini-slot, respectively.

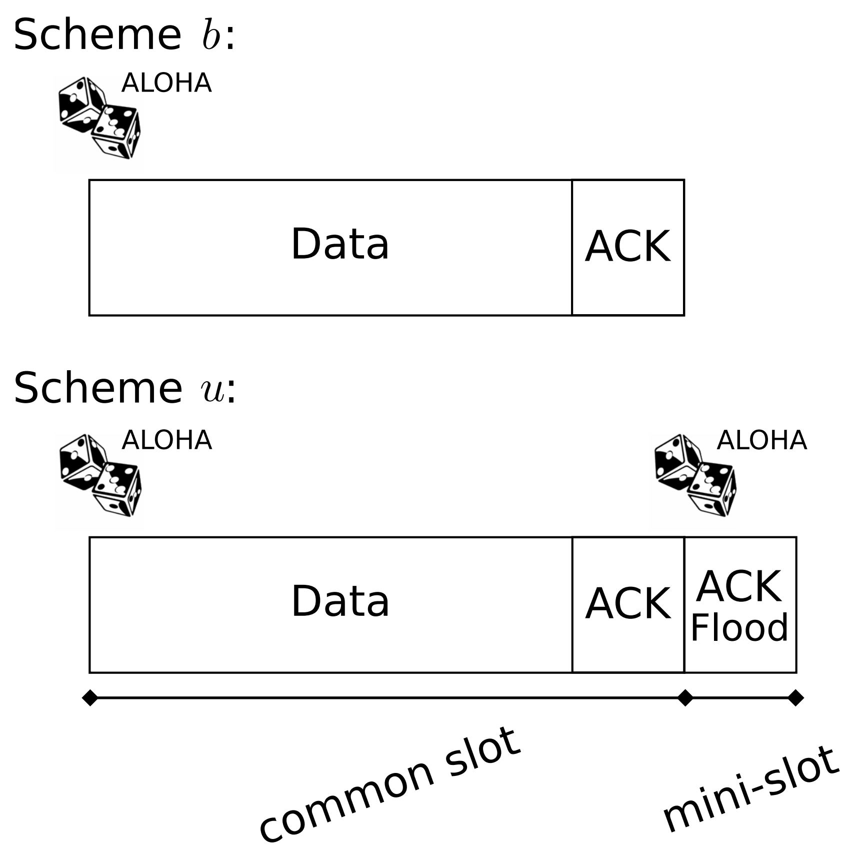


Figure 1: frame structure.

System Model

When a node gets a transmission opportunity it retransmits the packet transmitted on the previous ALOHA slot, or if this packet has already been ACKed it moves to a new packet.

A key characteristic that leads us to expect better performance for scheme u, is the fact that the amount of time between two transmission opportunities, for a certain transmitter, is large (with mean inversely proportional to p_{data}).

System Model – Metrics

- Expected delay of delivery over unit distance $\overline{D^m}$,
- Expected number of transmissions per packet delivery over unit distance $\overline{P^m}$,
- Throughput $\overline{T^m}$.

Note that $\overline{T^m}$ is analogous to $1/\overline{P^m}$ (i.e. the probability of a transmission to be successful), and we express it as follows.

$$\overline{T^m} = p_{\text{data}}/\overline{P^m}.$$

System Model – Formulation of the Optimization Problems

- One way to formulate the problem is to define an objective function which has the form $w\overline{T^m} - (1-w)\overline{D^m}$ with $w \in [0,1]$.

- Simulations, indicate that a certain assignment of values to the parameters of the system (i.e. the routing protocol and the ALOHA probabilities) for fixed α and β (i.e., as we will see, for fixed path loss function and SIR threshold), corresponds to the optimization of both delay and throughput for both schemes (that is, it optimizes $\overline{D^b}$, $\overline{T^b}$, $\overline{D^u}$ and $\overline{T^u}$ all at once).

System Model – Formulation of the Optimization Problems

On the square lattice network the available transmission ranges for each device are fixed and as such, we expect an optimal routing path towards a distant destination to be formed by links of equal length d.

Whereas in the case of the Poisson network, we rely on a greedy heuristic routing protocol which works as follows. If t is the transmitter, x_d the destination of the flow, and y the next hop, then the latter is determined by

$$\underset{y}{\text{argmax}}\{(1-q_d)c, \text{ where } d = ||t-y||,$$
$$c = ||t-x_d|| - ||y-x_d||\}.$$

Model Analysis – Interference

Let I be the interference to the node at the origin of a point process Φ. We have that

$$I = \sum_{k \in \Phi^*} l(||x_k||) 1_{\{k \text{ is on}\}}.$$

In our analysis we use the path loss function $l(x) = x^{-a}$, for $a > 2$.

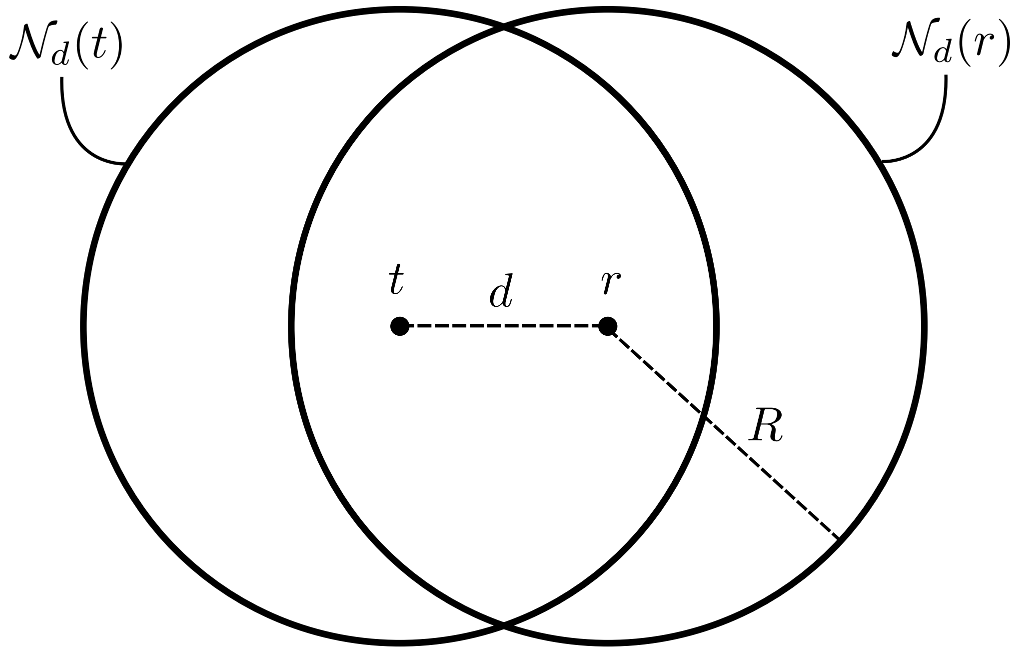
Model Analysis – Outage Probability

Let q_d denote the outage probability corresponding to the transmission from a node t to a receiver at the origin, where d is the distance from t to the origin. As outage probability is defined the probability that the receiver fails to receive the message, thus

$$q_d \equiv \mathbb{P}(\mathsf{SIR} < \beta) = \mathbb{P}\left(\frac{l(d)}{I - l(d)} < \beta\right).$$

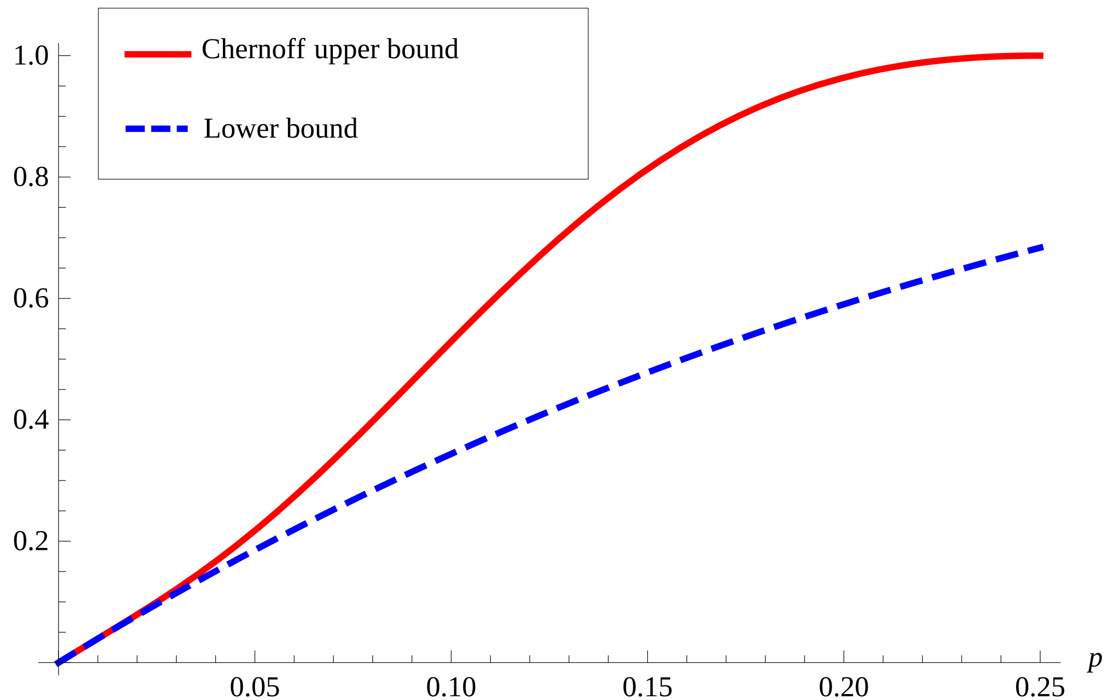
Model Analysis – Outage Probability

One technique that simplifies the analysis is to split interference to interference caused by near and far nodes.



Model Analysis – Outage Probability

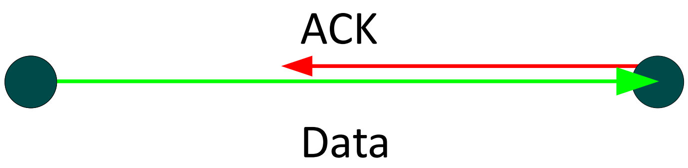
On the square lattice, through the use of the Chernoff bound, we bound q_d from above for $d = 1$. For $\alpha = 3$, we have the following upper and lower bounds.



Model Analysis – Probability of an Unsuccessful First ACK

Let ξ_r and ξ_t denote the events of failed outage at the forward and reverse paths, respectively.

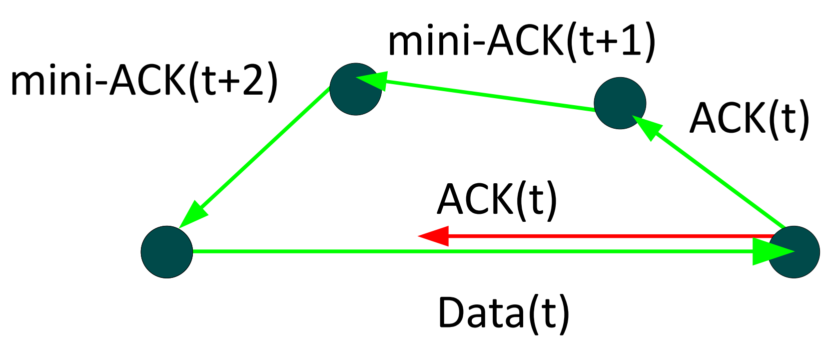
We define $\rho = \mathbb{P}\left[\xi_t | \overline{\xi_r}\right]$ as the portion of the transmitters that fail to get a successful ACK in the same common slot with the data transmission, conditioned on the fact that their respective receivers has successfully received the data packet.



Model Analysis – Probability of an Unsuccessful Flood ACK

Let V_k denote the event that k slots after a transmission that successfully reached its respective receiver, the corresponding ACK relayed through the flood (during the "mini"-slots) has not yet reached the transmitter. This is an event that interests us in the case where the ACK transmitted during the "common" slot failed to reach the transmitter, i.e when ρ holds. We define γ as the probability for a node getting a transmission opportunity before the ACK from the flood reaches the node. It is easy to compute γ as follows

$$\gamma = p\sum_{k=1}^{\infty}(1-p)^{k-1}\mathbb{P}\Big[V_k\Big].$$



Model Analysis – Probability of an Unsuccessful Attempt

Let ϕ_d^m denote the probability of an unsuccessful attempt for a link of length d; m denotes the scheme of communication used. An unsuccessful transmission is the result of the transmitter failing to receive an ACK from the receiver until the next ALOHA slot.

The derivation of an analytic expression for ϕ_d^m is tricky, mainly 'cause of the spatial correlation of the interference.

Model Analysis – Probability of an Unsuccessful Attempt

For scheme b we have

$$\phi_d^b = q_d + (1 - q_d)\rho,$$

where ρ is the probability of an unsuccessful first ACK.

While for scheme u we have

$$\phi_d^u = q_d + (1 - q_d)\rho\gamma,$$

where γ is the probability of a late ACK in case the first ACK was lost.

Model Analysis – Metrics

The expected delay of delivery over unit distance is given by

$$\overline{D^m} = \mathsf{E}_{x \in \Phi} \left[\frac{1 + \phi_d^m}{p_{\mathsf{data}}(1 - q_d) d} \right],$$

and the throughput by

$$\overline{T^m} = p_{\mathsf{data}} / \overline{P^m} = p_{\mathsf{data}} / \, \mathsf{E}_{x \in \Phi} \left[\frac{1}{(1 - \phi_d^m) d} \right].$$

Model Analysis – Performance Gain

For the case of the lattice network, we define the delay gain as

$$D_g \equiv \frac{\overline{D^u} - \overline{D^b}}{\overline{D^b}} = \frac{\phi_d^u - \phi_d^b}{1 + \phi_d^b} = -\frac{1-\gamma}{1 + \dfrac{1+q_d}{(1-q_d)\rho}},$$

and the throughput gain as

$$T_g \equiv \frac{\overline{T^u} - \overline{T^b}}{\overline{T^b}} = \frac{\phi_d^b - \phi_d^u}{1 - \phi_d^b} = \frac{\rho}{1-\rho}(1-\gamma).$$

Simulation Results – $l(d) = d^{-a}$

Square lattice network:

α	p^*	T_g	D_g	ρ	γ	q_d
2.3	1/20	4.5	−2.5	10	60	22
3	1/8	6.5	−2.5	11	49	40
4.5	1/4	7.5	−1.5	10	35	60

The reason behind this performance is that ρ (i.e. the probability of broken reverse path conditioned on the fact that the forward one is working) is small; specifically around 10%.

The results are even poorer for the Poisson network, and we conclude that in this setting the use of scheme u is not worthwhile.

Simulation Results – $l(d) = Zd^{-a}$

We assume a flat fading channel where the envelope is Rayleigh distributed, and thus the power is exponentially distributed. We define Z to be an exponentially distributed random variable with variance $\mathrm{Var}(Z)$. In this case ρ increases substantially which in turn results in an improvement in T_g and D_g.

Simulation Results – $l(d) = Zd^{-a}$

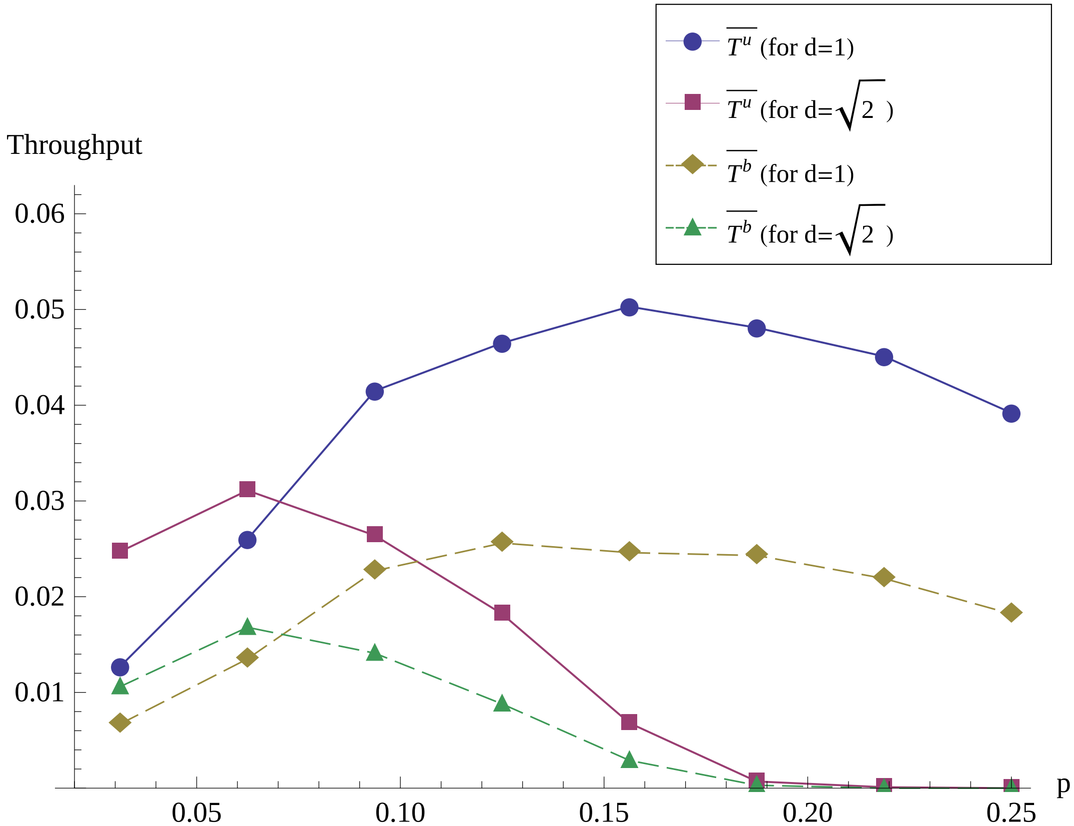
Square lattice network:

α	Var(Z)	p^*	T_g	D_g	ρ	γ	q_d
2.3	10^{-2}	1/16	83	−9	65	55	41
3	10^{-1}	1/8	81	−9	63	52	45
3	10^{-2}	1/8	81	−9	63	55	41
3	10^{-3}	1/8	83	−9	65	55	41
4.5	10^{-2}	1/4	116	−9	65	38	60

Poisson network:

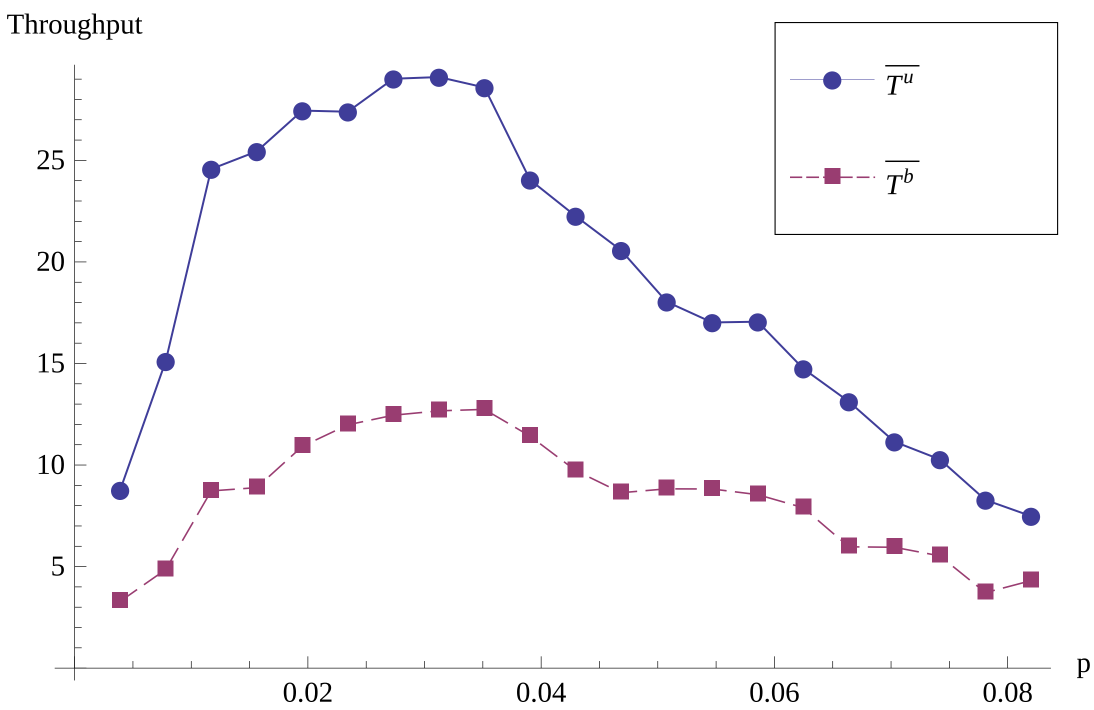
α	Var(Z)	p^*	T_g	D_g	ρ	γ	q_d
2.3	10^{-2}	1/26	148	−3	79	63	85
3	10^{-1}	1/34	142	−3	81	58	85
3	10^{-2}	1/32	135	−3	81	60	87
4.5	10^{-2}	1/56	132	−3	77	57	83

Simulation Results – $l(d) = Zd^{-a}$



$\overline{T^u}$ and $\overline{T^b}$ for $d \in \{1, \sqrt{2}\}$, on a lattice network with $\alpha = 3$, $\beta = 1$, and fading of variance 10^{-2}. Both schemes achieve their maximum throughput for $d = 1$ and the corresponding optimal p^* is around 1/8.

Simulation Results – $l(d) = Zd^{-a}$



$\overline{T^u}$ and $\overline{T^b}$ on a Poisson network with $\alpha = 3$, $\beta = 1$, and fading of variance 10^{-2}; using a fixed routing protocol. Both throughputs are optimized around $p^* = 1/32$.

Appendix follows.

Concurrent Optimization

For the case of the lattice network, we justify why the said assignment optimizes both delay and throughput under a certain scheme as follows. We have that

$$\overline{D^b} = \frac{1+\phi_d^b}{p(1-q_d)d} = \frac{1}{pd}\Big(\frac{2}{1-q_d} - (1-\rho)\Big).$$

Let us assume that $(1-\rho)$ is small compared to $2/(1-q_d)$. Then it holds that $\overline{D^b}$ is roughly proportional to $1/(p(1-q_d)d)$, which is a quantity to which $\overline{T^b}$ is clearly inversely proportional. Thus $\overline{D^b}$ is inversely proportional to $\overline{T^b}$, and as we want to minimize $\overline{D^b}$ and maximize $\overline{T^b}$, we can deduce that the two metrics are going to get their optimal values for the same set of parameters. In our simulations, it is the case that $(1-\rho)$ is small enough compared to $2/(1-q)$, in order for the above phenomenon to occur. An analogous statement holds for the case of $\overline{D^u}$ and $\overline{T^u}$.