Ad hoc TCP: achieving fairness with Active Neighbor Estimation

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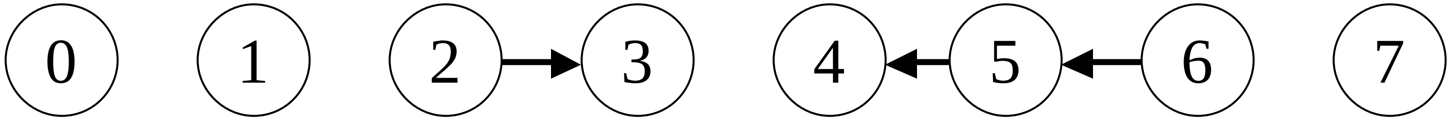
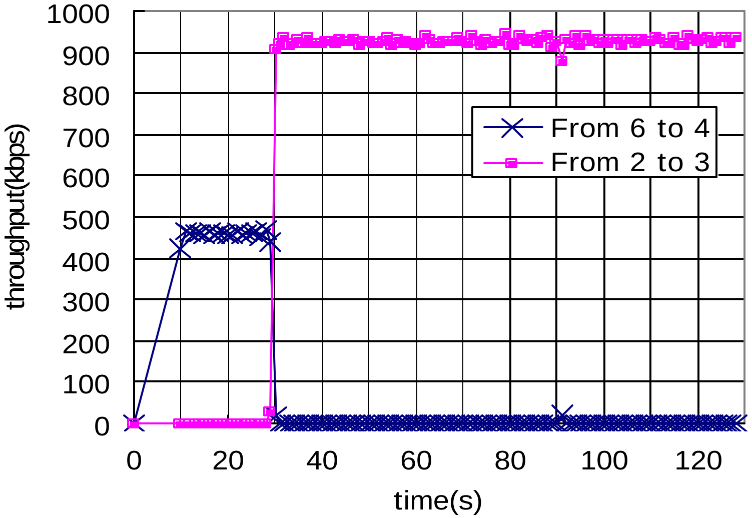
“Ad Hoc” TCP design challenge

- **802.11 Binary Exp Backoff (BEB) scheme: when multiple TCP connections share a common bottleneck, the interaction of 802.11 BEB and TCP causes unfairness**
- **Unfairness observed even with no mobility**
- **Unfairness can be extreme in certain ad hoc network scenarios: some TCP connections practically shut off while others achieve full throughput (ie, the latter capture the channel); aggregate throughput across connections remains constant**
- **Result: unfairness and capture lead to uneven, unpredictable performance of TCP flows – untenable in the battlefield and emergency recovery nets**

An NS-2 example of TCP “capture” with 802.11



- String topology, each node can only reach its neighbors
- First TCP session starts at time =10.0s from 6 to 4
- Second TCP session starts at 30.0s from node 2 to 3
- At 30.0s, the throughput of first session drops to zero: session (2,3) has captured the channel!



What causes unfairness/capture?

- Hidden and exposed terminal problems (explained later in detail)
- Large Interference range (usually larger than transmission range)
- Binary Exponential Backoff (BEB) of 802.11 tends to favor the last successful node
- TCP own timeout and backoff worsen the unfairness
- Lack of “cooperation” between TCP and MAC

Simulation environment

- QualNet 2.9
- Routing Protocol: static routing (no mobility)
- MAC protocol: IEEE 802.11 DCF (Distributed Coordination Function)
- Physical layer: IEEE 802.11b DSSS (Direct Sequence, Spread Spectrum)
- Channel bandwidth: 2Mbps
- TCP variant: New RENO
  - MSS = 512 byte;
- Application: FTP
- Simulation time: 350s

Experimental scenario

Trans. range = 376m
Dist(0,1) = Dist(2,3) = 300m

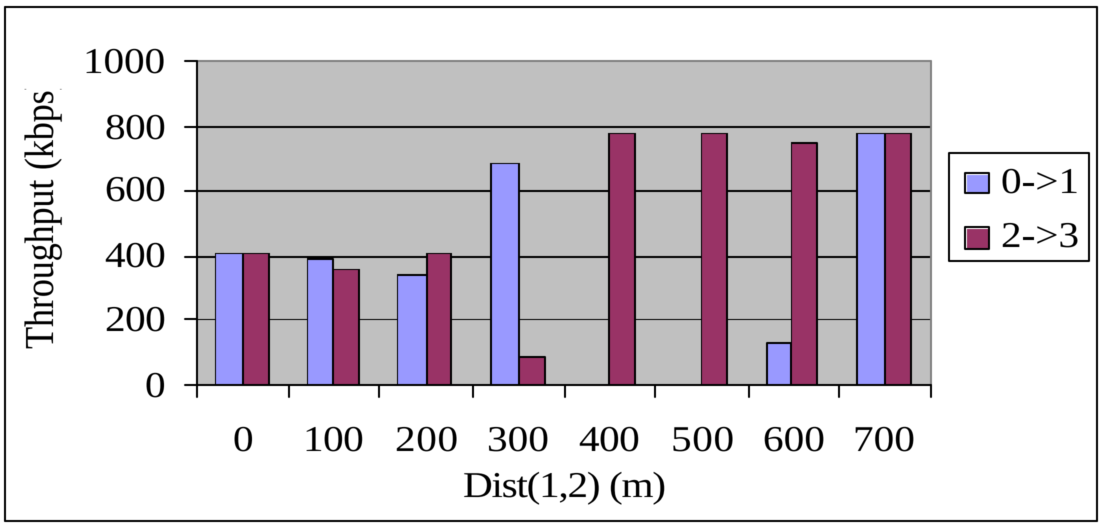
Hidden node: node 2 is hidden from node 0; but, it can interfere with the reception at node 1

Exposed node: node 1 is exposed to transmissions from 2 to 3; thus node 1 cannot transmit to node 0 while 2 transmits to 3

We will vary the distance Dist (1,2). Thus, different pairs of nodes are hidden and/or exposed to each other in different runs

Unfairness in simple TCP test case

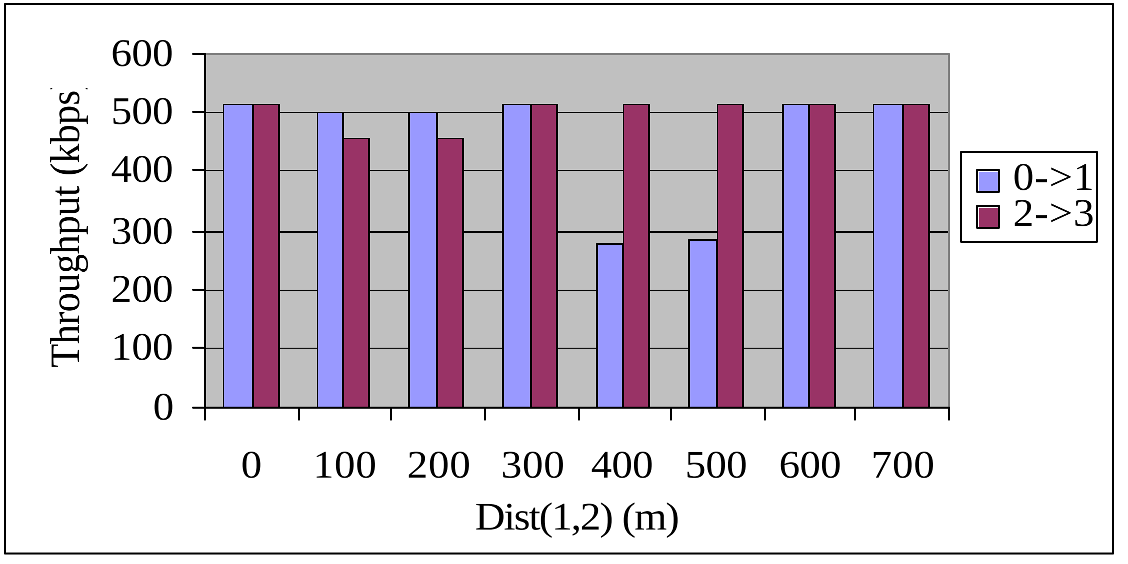
Trans. range = 376m
Dist(0,1) = Dist(2,3) = 300m



Throughput of FTP/TCP connections for variable Dist(1,2)
TCP Window = 1pkt

- **D < 300m; almost fair**
- **D = 300m; connection (0,1) dominates**
- **300 < D < 600, connection (2,3) dominates**

Unfairness in simple UDP test case



Throughput of CBR/UDP connections vs Dist(1,20
CBR connection time = 300s

- **UDP based CBR connections, instead of FTP/TCP**
- **Packet rate: 125 ppt as a video stream**
- **Conclusion: UDP unfairness not as severe as TCP**

Fact: radio ranges play key role in fairness

- Three radio ranges are of interest:
- Transmission range (TX_Range): represents the range within which a packet is successfully received if there is no interference from other radios
- Carrier sensing range (CS_Range): is the range within which a transmitter triggers carrier sense detection
- Interference range (IF_Range): is the range within which stations in receive mode will be "interfered with" by an unrelated transmitter and thus suffer a loss
- Relationship of three ranges
  - $TX\_Range < IF\_Range_{max} < CS\_Range$

Range models in QualNet and Ns2 simulators

	QualNet	NS2
Pathloss	Two-Ray	Two-Ray
SNR_Threshold	10	10
TX_Range	376m	250m
CS_Range	670m (= IF_Range_{max})	550m
IF_Range	1.78*d	550m

TCP unfairness: lessons learned

- Large window size worsens TCP unfairness/capture (in the sequel use will use W=1)
- The hidden and exposed terminal problem triggers TCP unfairness
- Large interference range also triggers TCP unfairness
- The BEB backoff scheme of IEEE 802.11 forces unnecessary, progressively increasing backoff in the handicapped nodes and thus leads to unfairness
- The larger physical carrier sensing range is helpful in preventing collisions; however its difference from the “virtual” carrier sense range (ie, RTS and CTS transmission range) may also worsen the unfairness in some situations

Proposed solutions

- In our research, we have developed and tested two solution approaches:
- New 802.11 backoff scheme: Active Neighbor Estimation (MAC level solution)
- Receiver Beam Forming (RBF) antenna (physical level solution)

TCP Unfairness: ANE Solution

- **Active Neighbor Estimation Based Backoff (ANE)**
  - Active Neighbor Estimation
    - An “active” neighbor list is maintained at each node
    - Each node passively counts # of active neighbors from “overheard” MAC packets (RTS, DATA)
  - Neighbor Information Exchange
    - A one-byte ANE field is appended to the MAC header of each packet, thus broadcasting ANE to all neighbors
    - Each node learns the # of “active” neighbors of its neighbors

TCP Unfairness: ANE Solution (cont)

– Backoff scheme

Let:

N = # of backlogged nodes competing with this transmitter

N_t = ANE at the transmitter; N_r = ANE at the receiver

Theory predicts (see Gallager and Bertsekas – Computer Networks) that the optimal retransmission probability is proportional to 1/(N +1), where N is the number of other stations competing with you

Transmitter does not know N, but can bound it as follows:

$MAX(N_t + N_r) <= N <= SUM(N_t + N_r)$

Note: the sets of active nodes for Transmitter and receiver are typically overlapped

TCP Unfairness: ANE Backoff Scheme

In 802.11, the Contention Window CW determines the retransmission interval. Backoff time is a function of CW.

In current 802.11, CW is doubled at each retransmission (BEB)

In the ANE implementation:

CW = aCWmin + aCWmin*N

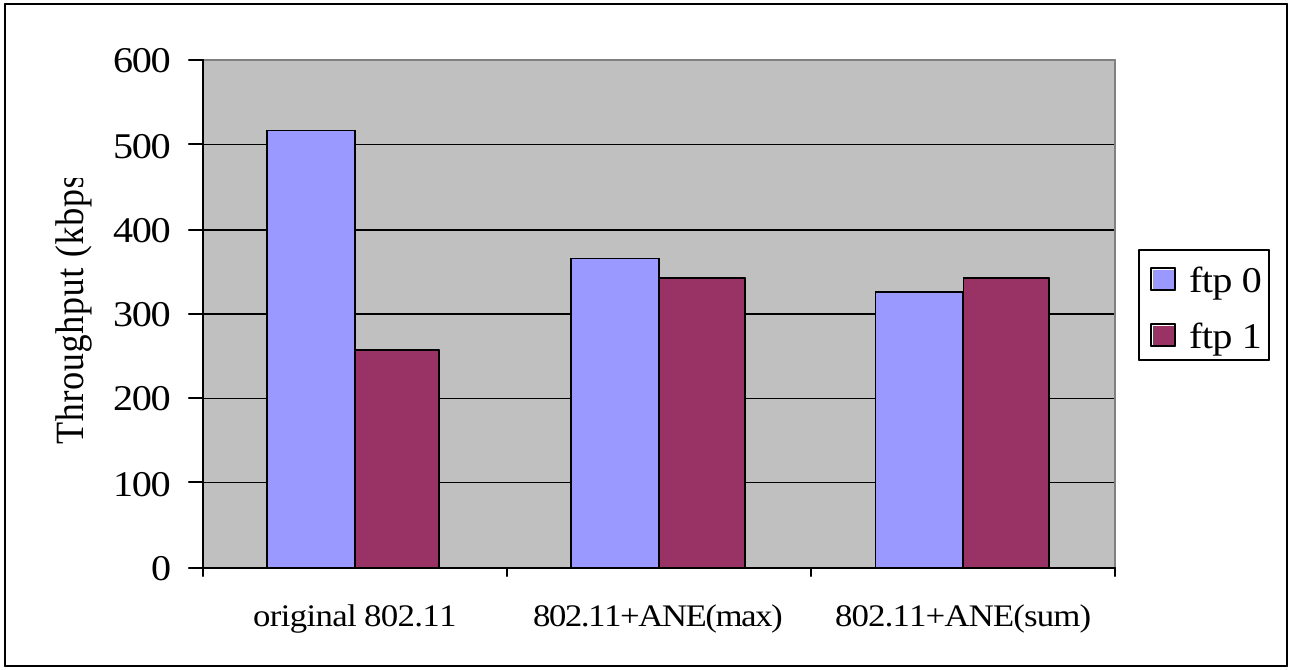
Backoff_Time = Random([0, CW]) x aSlotTime

where aCW_{min}, aSlotTime and Random() are variables or functions defined in the original 802.11 specs

Note: in the next aCWmin slots, each backlogged node has 1/(N +1) probability to transmit, as prescribed by theory

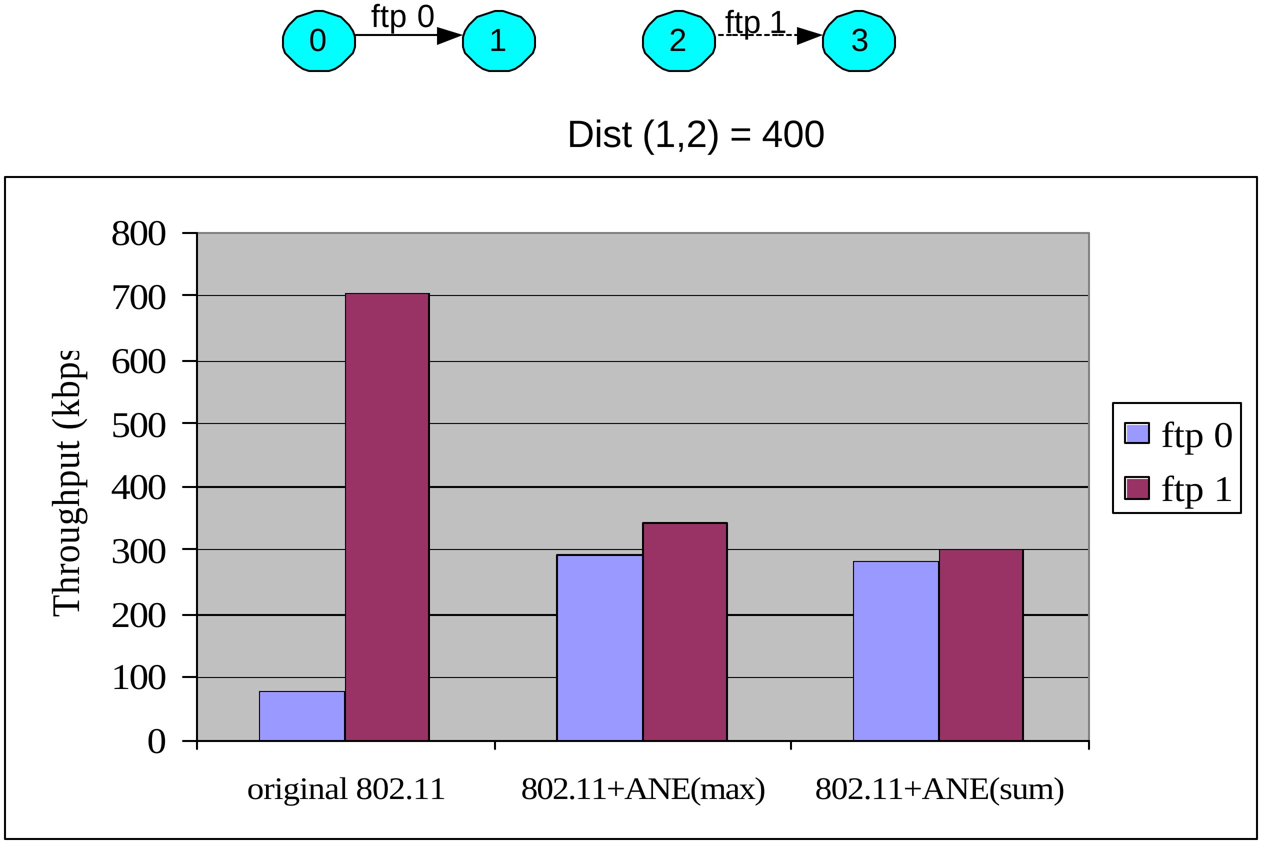
ANE evaluation: hidden and exposed terminals

Dist (1,2) = 400



FTP connections are in opposite directions

ANE evaluation: hidden and exposed terminals



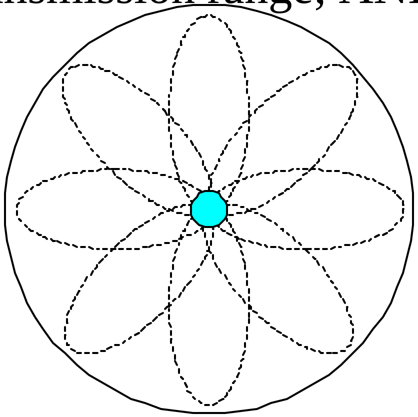
FTP connections are in same direction

Preliminary findings

- ANE works well in most situations, when the distance Dist (1,2) is small (in our case, Dist (1,2) < 300)
- If 300<Dist (1,2) < 600, the interference problem dominates over hidden/exposed terminal problem
- In spite of rate control enacted by ANE, two transmissions may still interfere with each other because of large interference range
- We introduce a physical level solution – Beam Forming Antennas

TCP Unfairness: Beam Forming Antennas

- Receiver Beam Forming (RBF) antennas
  - Targeting the **large** interference range problem
  - The RBF antenna can dynamically steer the beam and increase the gain in the direction of the incoming signal
  - Thus receiver can neutralize interference coming from the sides and from behind
  - This has the same effect as reducing the interference range to the transmission range; ANE can then handle the remaining problems



- A switched beam RBF antenna
- Number of patterns: 8
- Beam opening angle: 45^o degrees

TCP Unfairness: RBF (cont)

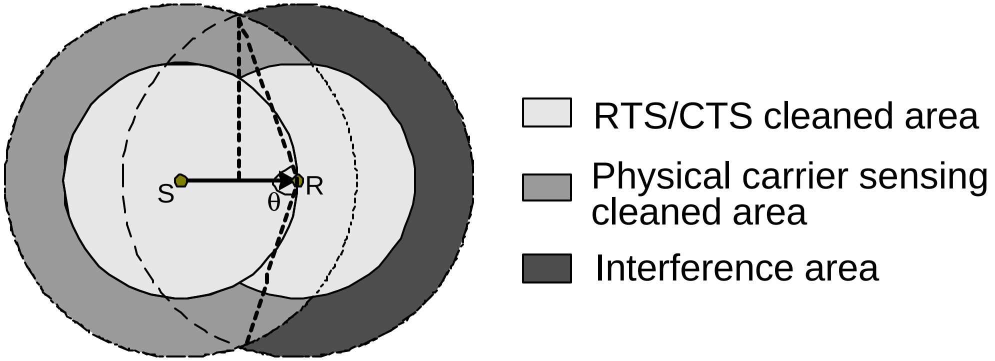
- Upper bound of the RBF beam angle required to block interference
  - Only nodes in the “black” Interference area can damage reception at node R
  - Let θ be the upper bound

    Cos(θ) = (d/2)/IF_Range, d is the distance between S and R

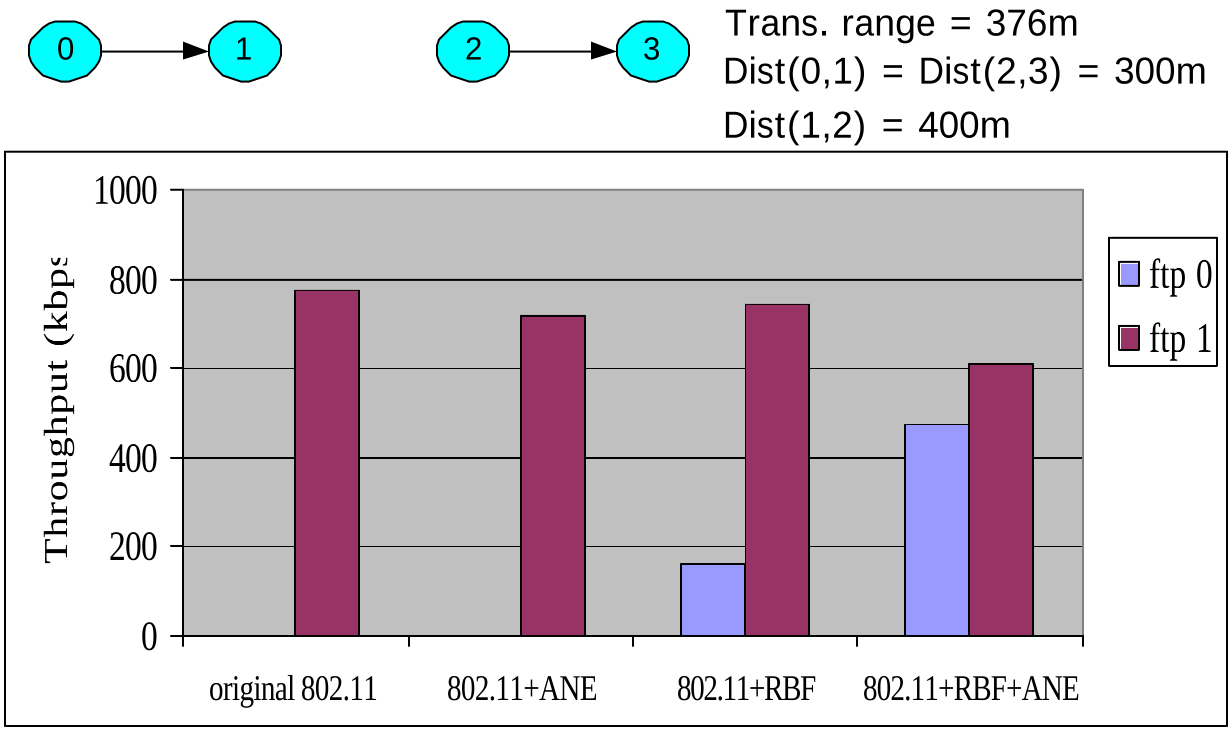
    IF_RANGE = 1.7*d (for Two_Ray path loss model)

    Cos(θ) = 1/3.4 => θ = arccos(1/3.4) = 72.9

Thus, even a very mild directivity (72.9º) can block interference!

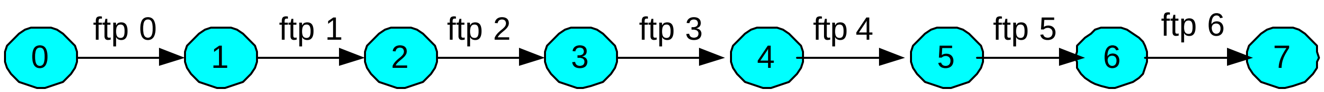


Evaluation of RBF solution

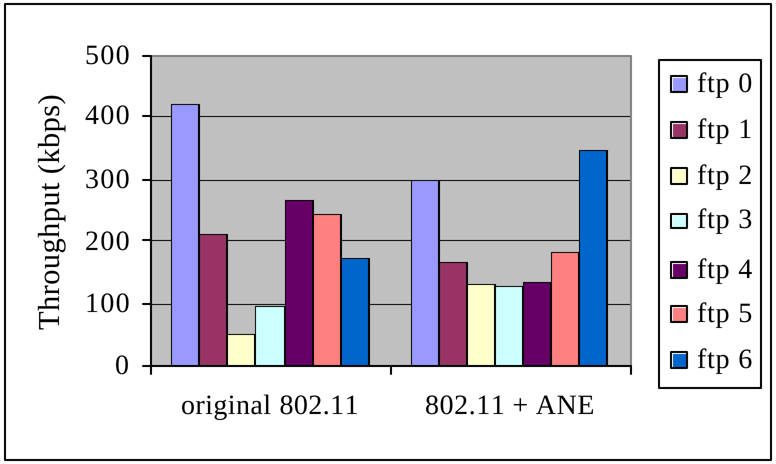


- **ANE is useless to unfairness caused by large interference range**
- **RBF antennas alone can prevent interference, but unfairness caused by hidden and expose terminals is still present**
- **ANE and RBF combined provide almost complete fairness**

Experiments in realistic network scenarios

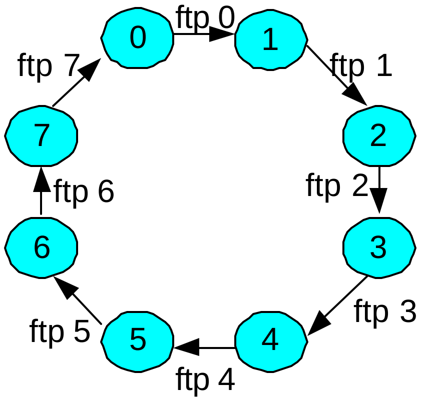


String Topology

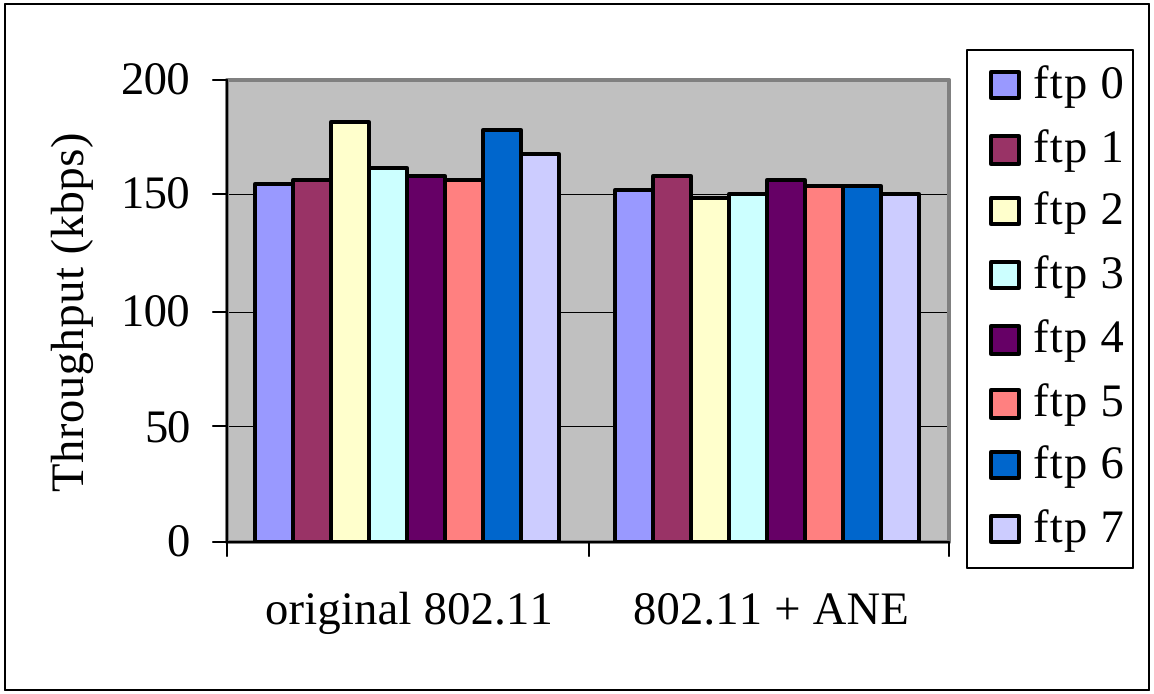


- **TCP connections between all adjacent pairs**
- **ANE restores fairness among all internal pairs**
- **End nodes have strong built in advantage that cannot be overcome even with ANE**

Network Experiments

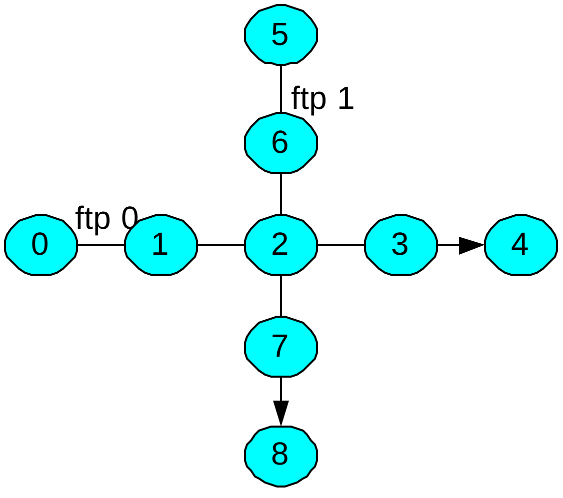


Ring Topology

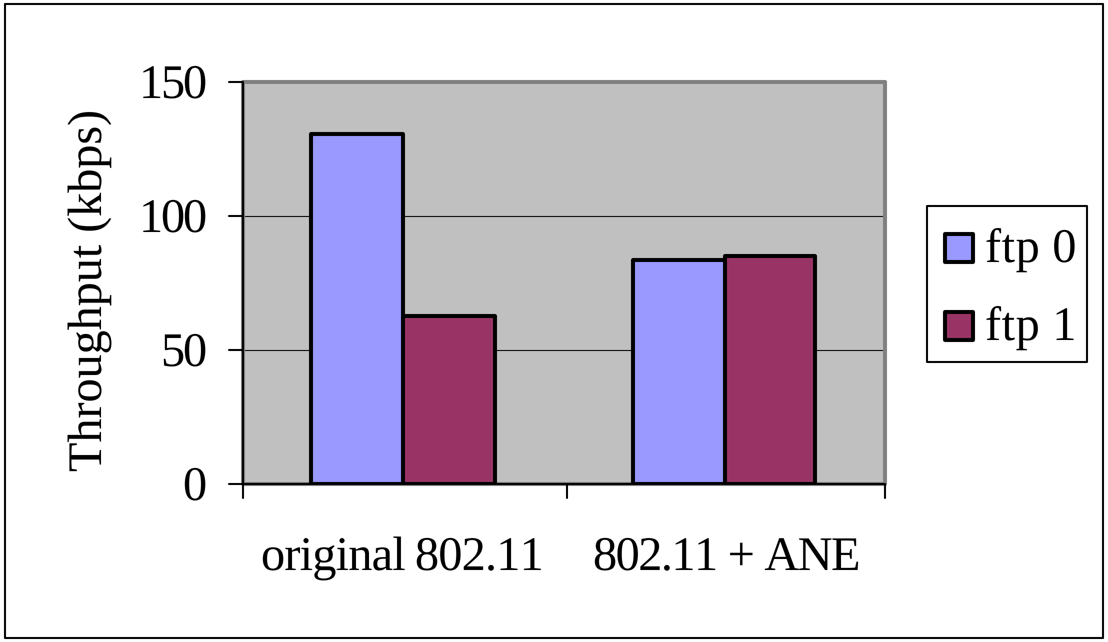


- **Original 802.11 scheme already quite fair**
- **ANE marginally improves fairness**

Network Experiments

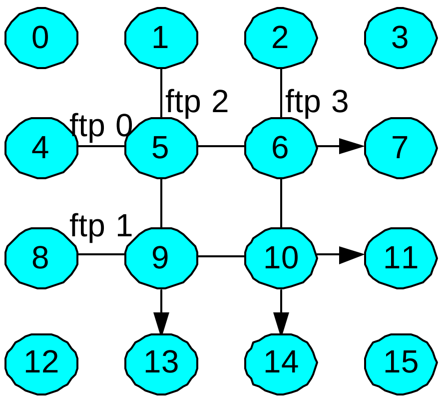


Cross Topology

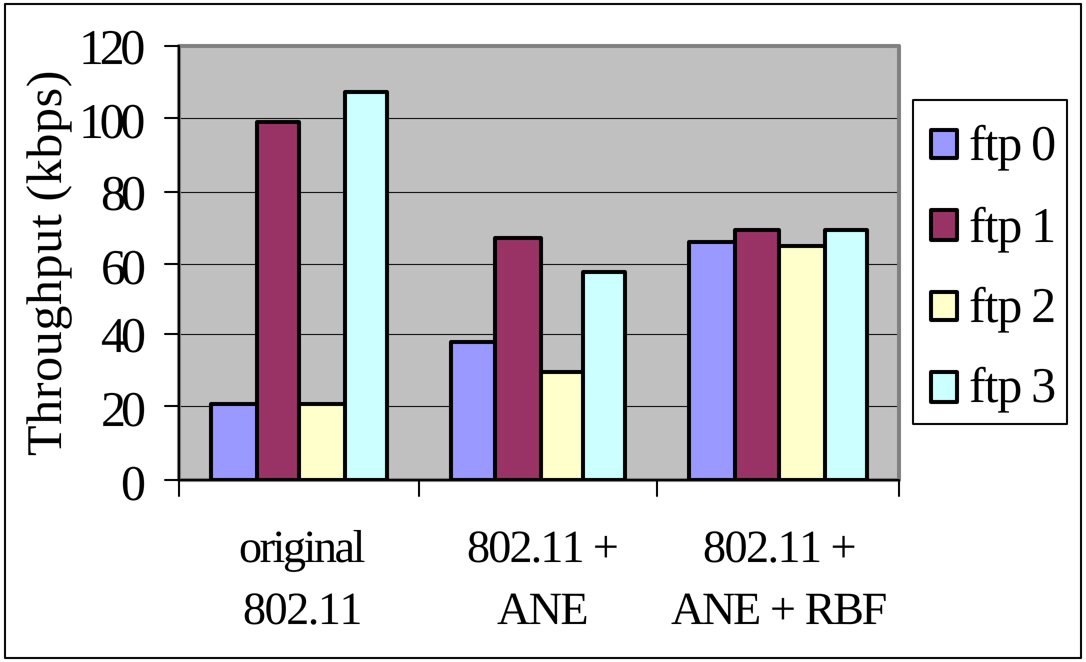


- TCP connections (0,4) and (5,8)
- ANE restores fairness

Network Experiments

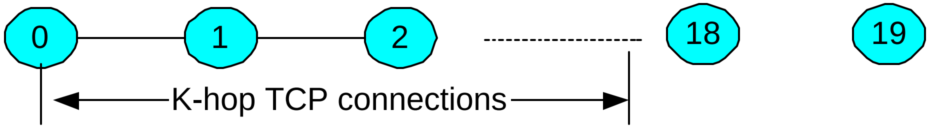


Grid Topology

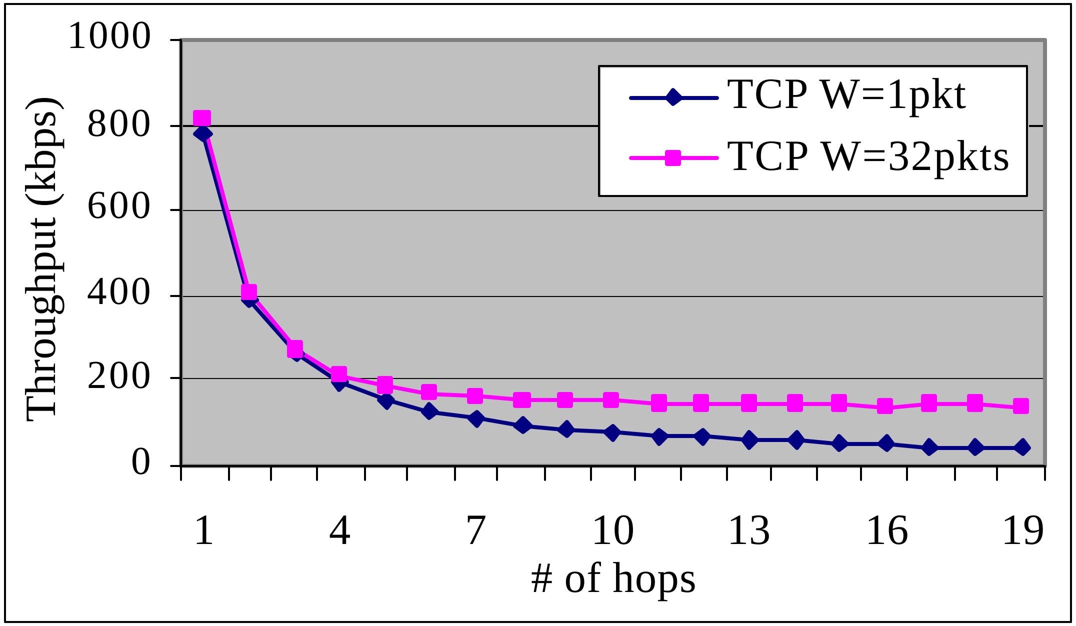


- **Four FTP/TCP connections across the grid**
- **Interference from distant transmitters has noticeable impact**
- **RBF antennas are required to fully restore fairness**

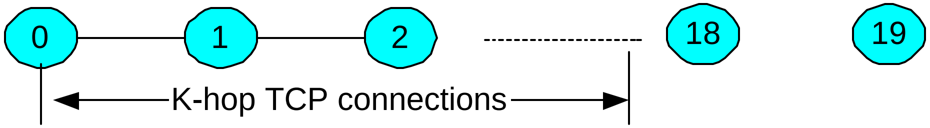
Impact of TCP window size: single TCP flow



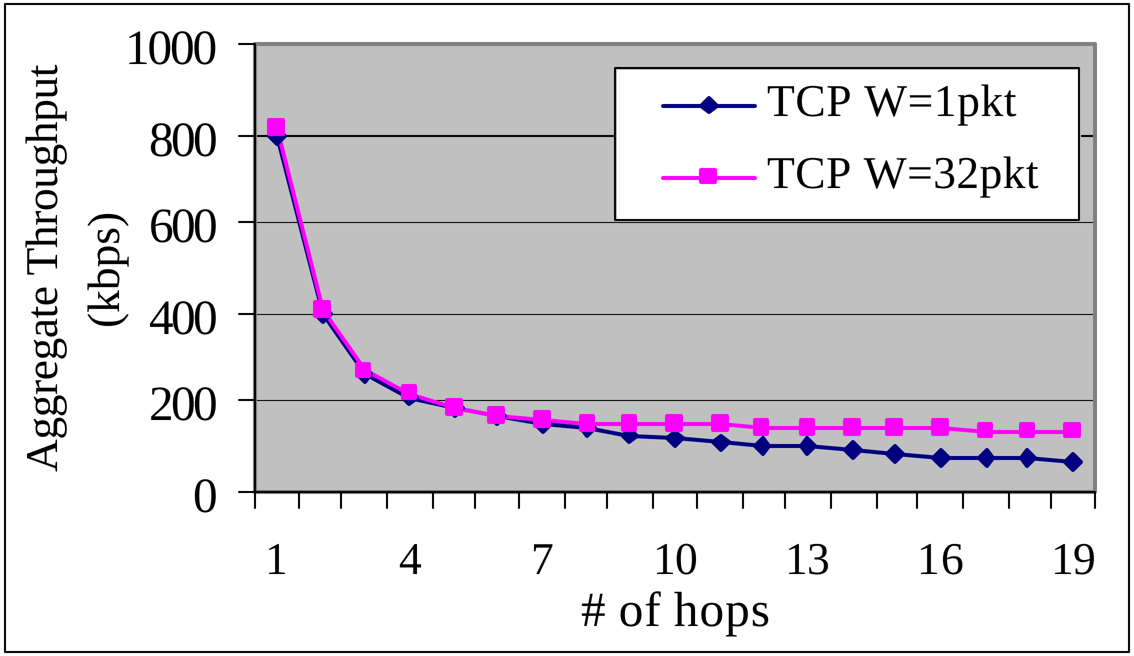
- **Only one connection: node 0 -> node K, k= 1, 2, … , 19**



Impact of TCP window size: two TCP flows



- **Two connections: 0 -> k and k->0, k= 1, 2, … , 19**



Impact of TCP window size

- With two competing flows, W =1 provides optimal throughput up to 8 hops
- As the number of competing flows increases, potential benefits of W>1 tend to vanish
- Moreover, as the number of flows increases, capture problems (not evident from previous aggregate throughput results) considerably worsen
- Recommended strategy: dynamically adjust W and set it to W=1 in ad hoc nets with competing TCP flows

Conclusions

- TCP unfairness/capture has been shown to occur in 802.11 ad hoc networks
- Capture can have a devastating effect on battlefield applications, virtually blocking/delaying TCP transmissions of critical imagery to weapon carrying UAVs and decision makers, for example.
- We have isolated the 802.11/TCP interaction problem from other previously studied problems (eg, mobility)
- We have developed MAC and Physical Layer solutions
- On going work: testbed measurements and implementation

Conclusions (cont)

- We have shown the key role played by the interaction of 802.11 Binary Backoff scheme and the TCP protocol own backoff mechanism
- Moreover, we have shown the strong dependence of fairness/capture on hidden and exposed terminal problems and on the various radio ranges
- We have proposed two solution -ANE and RBF antennas – that correct the problem and restore TCP fairness in all the scenarios we have tested.
- ANE requires a minor modification to 802.11 (in the Backoff algorithm); RBF requires no 802.11 modifications

Future work

- We plan to tie TCP max window setting to topology and contention information from the network layer (eg, # of hops, avg ANE values on the path,etc)
- We will integrate our solutions with other solutions proposed for the mobility and random interference problems
- We will run experiments with full mobility and random errors
- Finally, we will explore solutions that do not require 802.11 modifications; such solutions will rely on network and transport layer mechanisms
- In our testbed, we plan to acquire programmable 802.11 cards. With these, we will implement and run experiments with the ANE (instead of BEB) algorithm
- We will evaluate the impact of unfairness and "capture" on real applications with the "man in the loop"