Cross-Layer Performance Effects of Path Coupling in Wireless Ad Hoc Networks: Power and Throughput Implications of IEEE 802.11 MAC

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Abstract

Path coupling is defined as the media access contention between nodes distributed along node disjoint paths. It is caused by the broadcast nature of wireless communications. In this paper the cross-layer problem of path coupling is characterized and analyzed based upon the characteristics of the DCF of IEEE 802.11. Path coupling involves MAC-layer interactions that impact the performance of network-layer paths that are otherwise disjoint. These interactions are shown to have significant impact on energy efficiency, throughput and delay. Analytical models are developed to demonstrate the asymptotic throughput and power characteristics of coupled and non-coupled paths. These models are validated using simulation. The performance analysis of energy consumption and queuing characteristics at the network-layer due to MAC-layer interactions are also studied via simulation. Results demonstrate how path degrades performance, thus, supporting the need for the control of cross-layer interactions and methodologies for cross-layer optimization.

1 Introduction

A wireless ad hoc network is a self-organizing collection of *user* nodes that must cooperate in order to provide basic networking functionality. In general, the nodes of an ad hoc network are mobile and rely entirely on wireless transmission without any fixed infrastructure or dedicated communications devices. Consequently, packet-switched routing is required to manage limited device power, unpredictable variation in channel quality, and to reduce media access contention. Hence, an ad hoc network effectively consists of a set of mobile wireless routers. As such, the user nodes must participate in an adaptive routing algorithm that is responsive enough to meet application requirements without over-utilizing limited resources.

Applications for ad hoc networks range from rapidly deployable networks for military and civil operations, to networks of intelligent sensor devices. Sensors are typically power constrained and may be required to operate under extreme conditions for extended intervals of time without intervention. Ad hoc networks may also be utilized commercially to increase the capacity, range and quality-of-service of infrastructured wireless networks, and to support intelligent highway systems. To achieve their full potential, however, many challenges remain unaddressed or incompletely resolved, namely, scalability with respect to size and mobility, power efficiency and control, efficient multicast routing, improved transport-layer effectiveness, cross-layer inter-action and optimization, security and service availability.

The central theme of this paper focuses on a cross-layer approach to understanding and improving power efficiency and throughput based on the abstract notion of "path-coupling". This phenomena is caused by the broadcast nature of the wireless communications "link", wherein, multiple nodes contend for access to a single frequency channel or code sequence (in the case of CDMA). Specifically, this paper addresses performance implications for a wireless ad hoc network routing algorithm that relies on any of the class of contention based MAC-layer protocols. Given these circumstances traffic routed along link and node disjoint paths may be subject to transmission delays and packet loss due to contention with a neighbor for the channel or competition from hidden terminals.

Results presented in this paper suggest that the effects of path-coupling may seriously degrade network performance. As such, the cross-layer implications are clear: the MAC-layer should be able to measure the "degree of coupling" and report it to the routing-layer. Knowledge of traffic flows and path coupling could provide criteria for improved route selection that reduces energy consumption and increases throughput to acceptable levels. The sequel formulates the problem in terms of maximum-flow and minimum cost.

The remainder of this paper is organized as follows: In Section-2 the problem of path-coupling and its relationship to the MAC-layer are discussed. An analytical model is derived to improve understanding of the problem and show asymptotic results for network throughput and power consumption in Section-3. Simulation results shown in Section-4 are used for analysis of throughput and energy performance, and preliminary analysis of queuing behavior with respect to path coupling. Finally, conclusions and discussion of implications presented in Section-5.

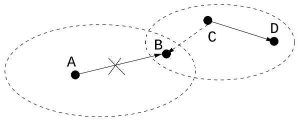
2 Overview

Numerous MAC layer protocols have been developed for wireless systems [13]. These include basic Carrier Sense Multiple Access (CSMA), Multiple Access with Collision Avoidance (MACA), Floor Acquisition Multiple Access (FAMA) and IEEE 802.11, which is based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). The analysis performed in this paper is based on IEEE 802.11 which is simple to implement and has been shown to exhibit superior performance to the other aforementioned protocols when utilized in conjunction with on-demand ad hoc network routing [13]. This selection was made, without loss of generalization, as a representative example of a class of algorithm—Industry standardization, widespread application in ad hoc network testbeds and simulation analysis make IEEE 802.11 an appropriate choice.

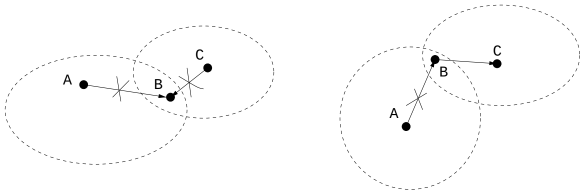
Batteries represent the sole power source for most wireless devices. However, technology for increasing battery lifetime relative to weight and cost advances less rapidly than that of other components that comprise a mobile computing platform, for example, transceivers and Digital Signal Processors (DSP). Hence, advances in battery technology alone are insufficient to ensure robust operation of ad hoc networks—energy must be conserved. As such, multi-tiered methodologies are needed that involve energy efficient devices, power saving systems software *and* applications, adaptive transmission systems and power conserving network algorithms designed to minimize power consumption.

2.1 Path Coupling

In this paper the problem of power conserving network algorithms is considered from a cross-layer perspective. Namely, the two-way interaction between the MAC-layer and routing, which leads to the coupling of independent network-layer paths is analyzed from the perspective of future cross-layer optimization. The problem involves transmission "interference" between two "independent" pairs of nodes resulting from MAC-layer handling of hidden terminals and direct contention with a neighbor for a shared broadcast channel. Spatial reuse of a single radio channel is the underlying cause of this phenomenon referred to in this paper as "path-coupling".



(1) hidden terminal problem



(2) Direct Interference

(3) Self Interference

Figure 1: Factors affecting path-coupling

Figure-1 illustrates the main factors that influence the coupling phenomenon: hidden terminals, direct interference and self interference. Exposed terminals (not illustrated) also cause problems because transmitters sense the channel, yet, collisions occur at the receiver. All these *problems* are handled by the MAC-layer protocol. However, both unavoidable realities of wireless communications and uncertainty require conservative behavior and lead to sub-optimal performance. In subfigure (1) Nodes A and C are hidden terminals with respect to one another—the link between B and C is a cross-layer "coupled linkage". Although the medium may be sensed idle by the transmitting station, it may not be idle near the receiver due to the (time) overlapping transmission from of second transmitting station that is out of range of the first. In this case, the second transmitter is a "hidden terminal" with respect to the first.

2.2 IEEE 802.11 MAC

The IEEE 802.11 committee standardized MAC and physical-layer protocols for wireless LANs. MAC-layer functions are carried out using CSMA/CA. The physical media considered by 802.11 is shared and subject to limited transmission range. The 802.11 committee introduced the terminology of an "ad hoc" wireless LAN that supported direct peer-to-peer

MAC communication without a centralized Base Station (BS). Ad hoc operation is supported by the Distributed Coordination Function (DCF) of 802.11. Thus, only the DCF is considered in the remainder of this paper. For a detailed description of 802.11 and the DCF readers are referred to [4].

The literature contains a large body of work focused on the performance of IEEE 802.11 LANs. In [2],[3],[4] analysis focused on the PCF, hence, lacks specific relevance to ad hoc networks. Recently, however, discouraging performance results for several ad hoc routing protocols [5] have drawn attention to the MAC issue. The analysis of the effects of different MAC layer protocols to specific ad hoc network routing algorithms was presented in [13]. This approach may be prone to bias and interaction with respect to the routing algorithm; furthermore, there is no explicit investigation of path-coupling, nor its effects on energy efficiency and throughput . The issue of 802.11 feasibility for ad hoc networks is directly addressed in [14]; however, the results are based on TCP performance over DSR, hence, do not provide clear distinction among the effects, nor can they provide any general result attributed to MAC/routing layer interaction. Most recently, [11] reports the interesting result: " 802.11 MAC protocol manages $\frac{1}{7}$ of the single-hop throughput, " which agrees in principle with the results reported here. However, the authors conclude that this result is the key factor affecting the ultimate feasibility of ad hoc networking. They fail to identify the coupled linkage aspect as a unique explanation of the problem and furthermore, nor to suggest the possibility of MAC-aware routing, cross-layer optimizations or alternative access control strategies. Whereas, the present analysis identifies "path coupling" and clearly shows the impact of cross-layer interaction between the MAC and routing layer. A possible methodology for leveraging knowledge of this interaction to optimize throughput using MAC layer information for routing is also suggested.

3 Ad Hoc Network Model

This section presents the network model. The major assumptions are explained and notation is defined. The remainder of the section focuses on the development of models for asymptotic analysis of throughput and energy consumption

The topology considered consists of a finite number of stations uniformly distributed throughout a BSS [3], [11]. The following justified assumptions improve analytical tractability without loss of generality:

- The effect of propagation delay is insignificant with respect to frame transmission time and media access delay; hence, it is negligible in the analysis. This is a very realistic assumption for transmission ranges ≤ 250m [4].

- Only a single ad hoc network consisting of one BSS is considered. Hence, it is assumed there are no interfering BSSs—the DSSS spreading sequence is unique [4].

- Collisions caused by simultaneous transmission are assumed to be the most significant cause of packet corruption. Hence, the effects of other error sources, including channel noise and multipath fading are assumed to be negligible with respect to the collisions.

- Node mobility is assumed negligible with respect to frame transmission time [11]. Hence, transmissions always complete before a mobile receiver moves out of range.

- Routes are assumed to remain static during the interval of interest. Thus, results generalize to any routing algorithm and analysis focuses on fixed cross-layer interactions.

As an example of a random network model, consider a topology consisting of 12 nodes that are divided into two 6-hop node *disjoint* paths: (0,1,2,3,4,5) and (6,7,8,9,10,11). These paths are coupled by linkages that *join* nodes 2 to 7 and nodes 3 to 8. Simultaneous traffic flows consisting of *i.i.d* arrival distributions are routed along the two paths subject to coupling interference.

3.1 Asymptotic Analysis of Throughput

The analysis of throughput consists of two steps: First, an upper-bound is derived for the case without path-coupling. Next, the effects of path-coupling are incorporated into the model, this is achieved in two steps: First, an upper bound is derived for a communication link with no hidden terminal. Next, an upper bound for throughput when there is hidden terminal present is derived. The notation used in the analysis is defined in Table-1.

STEP 1: In this step throughput is computed for the case when there is no path coupling. Based on the RTS/CTS scheme it should be understood that when a pair of nodes are communicating with each other over a multihop path, the uplink and downlink nodes can not transmit or receive data simultaneously. Consider the first path in the random topology discussed

Notation	Meaning
T_{obs}	Observation time
L_{max}	Maximum data frame length
T_{RTS}	RTS frame transmission time
T_{CTS}	CTS frame transmission time
T_{ACK}	ACK frame transmission time
T_d	DATA frame transmission time
Thr	System throughput
D_{rcv}	Data received during observation time
P_{rcv}	Frames received during observation time
$\#_{hop}$	# of hops in the path
$\#_{hid}$	# of hidden terminals along path

Table 1: Required notation

previously: Node 0 can reliably transmit a new packet to node 1 only after node 2 completes its transmission of a previous packet to node 3 (Assuming no queuing or processing delays at the nodes). Accordingly, it can be concluded that a new packet transmission can occur no earlier than the completion of first 3 hops of the previous packet.

In order to evaluate maximum throughput, maximum length data frames are assumed in the following expressions. The throughput of the system is defined as the amount of data successfully transmitted from the source to the destination:

$$\frac{\text{number of successful transmissions} \times L_{max}}{T_{obs}}$$

Assuming ideal conditions in which transmission is error-free and a single frame is transmitted, Equation-1 expresses the total time required to successfully transmit one frame over a single hop:

$$\begin{aligned} DIFS &+ T_{RTS} + SIFS + T_{CTS} + \\ SIFS &+ T_d + SIFS + T_{ACK} \end{aligned} \tag{1}$$

next, define the interval T_r as follows:

$$T_r = DIFS + T_{RTS} + 3 \times SIFS + T_{CTS} + T_{ACK}$$

The following Lemma estimates the upper bound on throughput in the case when there is no path-coupling:

Lemma 1 *Let T_r be a given constant transmission rate that is independent of the the data frame length and let the factor e^6 accommodate differences in units (assuming the time units are given in μs, and the units for load and throughput are bit/s). The* asymptotic upper-bound on system throughput *is given by the following expression:*

$$\begin{aligned} thr &= \frac{D_{rcv}}{T_{obs}} \\ D_{rcv} &= L_{max} \frac{T_{obs} - max(0, \#_{hop} - 3)(L_{max} + T_r)}{min(3, \#_{hop})(L_{max} + T_r)} \\ thr &= \frac{L_{max} \times e^6}{min(3, \#_{hop})(L_{max} + T_r)} bits/s \end{aligned} \tag{2}$$

Lemma-1 provides an upper bound for system throughput when load exceeds the capacity of the network. When the load remains significantly less than the maximum system throughput, theoretically every transmitted frame will be received, hence, the throughput will approach the load. To account for transmission pipelining, which is only possible for paths consisting of three or more hops, min and and max functions have been added to the result in Equation-2. In practice, the maximum achievable throughput (under the current assumptions) depends significantly of the number of nodes in the system and the maximum data length a data frame can transmit.

STEP 2: In this second case path coupling is considered in the evaluation of throughput. Figure-2 depicts an example that can be use to understand the derivation: assume all nodes are in constant backlog. When node A is transmitting to node B, the node coupled with B, node E, which is hidden with respect to node A, must defer its transmission/reception. Whereas, if there is no coupling, E may transmit/receive simultaneously.

Following transmission, node E should continue to defer allowing node B to transmit downstream to node C. Alternatively node E could access the link to transmit or receive; however, node B must defer in this case. According to 802.11 nodes that defer transmission must backoff for an interval that exceeds the transmission time of the interfering node (NAV). In the following derivation it is assumed that backoff times are equal to the NAV. Given either case, the delay incurred due to coupling is always at least twice $T_r + T_d$.

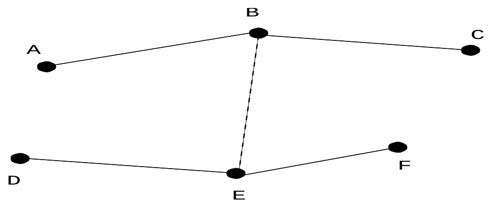


Figure 2: Example of network with hidden terminal

Based on the previous discussion it should be clear that the effect of the path coupling can be expressed as a "virtual load" imposed on a hidden terminal (or neighbor), thus increasing delay and decreasing system throughput. The following Lemma estimates the upper bound on throughput accounting for the virtual load resulting from path-coupling:

Lemma 2 *Consider two disjoint routes with coupled linkage(s) between them. For each coupled linkage, the time to transmit a frame will increase by at least twice* $T_r + T_d$ *versus no coupling case. Throughput without the presence of a hidden terminal is given by Lemma-1. However, to correct for the virtual load the received data remains fixed while* T_{obs} *is increased. The asymptotic upper-bound on system throughput accounting for path coupling is given by the following expression:*

$$\begin{aligned}
thr &= \frac{D_{rcv}}{T_{obs}} \\
P_{rcv} &= \frac{D_{rcv}}{L_{max}} \\
&\approx \frac{T_{obs}}{min(3, \#_{hop})(L_{max} + T_r)} \\
T_{obs} &= T_{obs} + P_{cv}(T_r + T_d) \times 2 \times \#_{hid} \\
thr &\approx \frac{\frac{T_{obs} - (L_{max}+T_r)max(0, \#_{hop}-3)}{(L_{max}+T_r)min(3, \#_{hop})} L_{max}}{T_{obs} + 2\#_{hop} \frac{T_{obs} - (L_{max}+T_r)max(0, \#_{hop}-3)}{(L_{max}+T_r)min(3, \#_{hop})}}
\end{aligned}$$

As a numerical example consider the model used in this paper: the network consists of two 6 node paths as described previously. For this case the throughput of each path can be expressed according to the following:

$$\begin{aligned}
thr &\approx \frac{\frac{T_{obs} - (L_{max}+T_r)\times 2}{(L_{max}+T_r)\times 3} \times L_{max}}{T_{obs} + \frac{T_{obs}}{(L_{max}+T_r)\times 3} \times (L_{max} + T_r) \times 2 \times \#_{hid}} \\
&\approx \frac{\frac{L_{max}}{(L_{max}+T_r)\times 3}}{(1 + \frac{2}{3} \times \#_{hid})} \qquad (3)
\end{aligned}$$

3.2 Power Consumption Model

Power consumption is difficult to quantify due to a large number of system parameters and implementation factors. This subsection presents an energy model in which each node can be in one of four states: idle, backoff, transmit or receive. Carrier sensing is done in idle state. Based on results presented in [9], the following power ratio can be defined for these states: *idle : backoff : transmit : receive* = 1 :1 :1.4 :1.05. As such, it is necessary only to know the percentage of time during which a node is in the *transmit* or *receive state.*

The total time spent in each state is a random variable. Hence, by using assumptions similar to Subsection-3.1 this energy model estimates a *lower-bound* on the total power consumption. Equation-1 determines the time spent in each state. Computation of the total power consumed in the network requires knowledge of the packet transmission rate (to determine the total number of packet transmissions by each node), and the mean path length—source, destination and intermediate nodes consume power at different rates. The following Lemma characterizes the lower-bound on energy consumed by the system:

Lemma 3 *Let* T_{tran} *be the total time spent in packet transmission and the following variables represent the power consumed by intermediate, source and destination nodes respectively:* $Power_i$,$Power_s$,$Power_d$. *Then the total Power,* $\mathcal{P}$, *consumption is given by the following expression:*

$$\mathcal{P} = Power_s + Power_d + (\text{\# of nodes -2}) \times Power_i$$

$Power_i$,$Power_s$,$Power_d$ *are expressed as follows:*

$$\begin{aligned}
T_{tran} &= RTS + DATA + CTS + ACK \\
T_{rcv} &= RTS + DATA + CTS + ACK \\
T_{other} &= T_{obs} - P_{rcv} \times (T_{tran} + T_{rcv}) \\
Power_i &= T_{other} \times 1 + T_{tran} \times 1.4 + T_{rcv} \times 1.05
\end{aligned}$$

$$\begin{aligned}
T_{tran} &= RTS + DATA \\
T_{rcv} &= CTS + ACK \\
T_{other} &= T_{obs} - P_{rcv} \times (T_{tran} + T_{rcv}) \\
Power_s &= T_{other} \times 1 + T_{tran} \times 1.4 + T_{rcv} \times 1.05
\end{aligned}$$

$$\begin{aligned}
T_{tran} &= CTS + ACK \\
T_{rcv} &= RTS + DATA \\
T_{other} &= T_{obs} - P_{rcv} \times (T_{tran} + T_{rcv}) \\
Power_d &= T_{other} \times 1 + T_{tran} \times 1.4 + T_{rcv} \times 1.05
\end{aligned}$$

A more precise model is being studied, wherein, an expression is derived for the expected value of packet retransmissions. This value depends on coupling and load. At the present time precise power ratios can only be determined via simulation. Simulation results are presented in next section.

4 Simulation Model and Analysis

A discrete event simulation model was developed in CSIM [1] to validate the asymptotic results developed analytically in the previous section, and to analyze system performance under different coupling conditions and path lengths. Pseudo-parallel processes

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[1] CSIM is a simulation engine consisting of a pre-processor and library of functions for simplifying the development of process-oriented simulators.

Parameter	value
DIFS	$50 \mu s$
SIFS	$10 \mu s$
RTSTIME	$160 \mu s$
CTSTIME	$112 \mu s$
ACKTIME	$112 \mu s$
DATATIME	data lengh in bits + 224 μs
Buffer Size	300 frames
Max data length	1600
parameter of geometric distribution	$6.25e^{-4}$

Table 2: Simulation Parameters

managed by the CSIM simulation engine make it possible to effectively model complex systems with reusable components.

Each node was modelled by a separate process encompassing MAC-layer and routing functions, while the system workload (traffic) was generated by each source node's traffic process. The traffic arrivals were modelled as a Poisson process; however, packet lengths were distributed according to a truncated geometric distribution. The data length was truncated to ensure it would not exceed the maximum data length specified by the protocol. Based on the same justification as [11] the analysis is focused on *static* ad hoc networks.

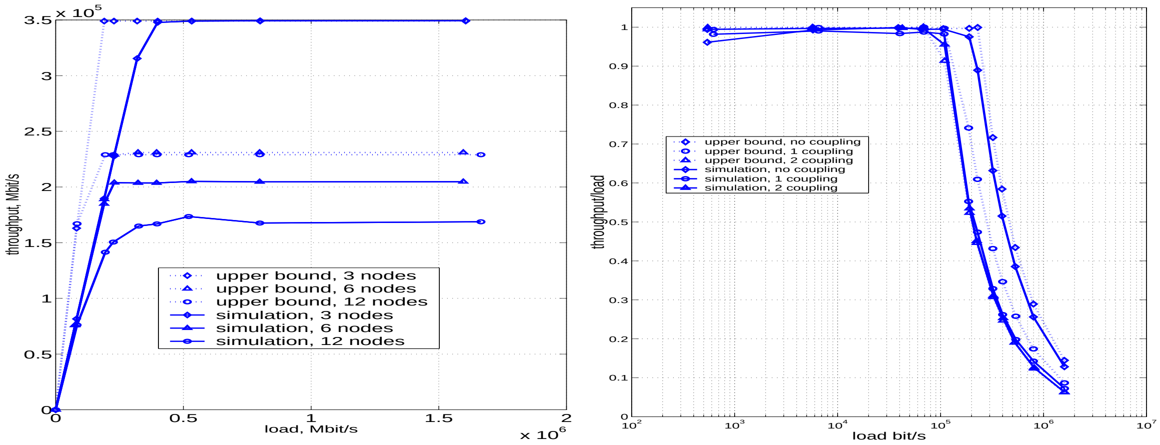
Table-2 shows the parameters used in the simulation (see [4]). Each simulation ran for 100 seconds and was repeated 15 times. The values of RTSTIME, CTSTIME, ACKTIME and DATATIME in Table-2 were computed under the assumption of a 1 Mbps transmission rate. According to Lemma 1 and Lemma 2 the theoretic upper-bound for throughput can be evaluated for different size systems. For example, assuming no path coupling and path lengths of 3, 6 and 12 nodes, the upper-bounds are 0.349 Mbps, 0.231 Mbps and 0.229 Mbps respectively. While with one and two path couplings, the upper-bounds on throughput for a 6-node path are found to be 0.139 Mbps and 0.1 Mbps respectively.

4.1 Asymptotic Model Validation

The objective of the first set of experiments was to utilize simulation to validate the asymptotic model. Analytical and simulated throughput versus load curves were generated under steady-state conditions utilizing different path-length and coupling scenarios. Path length was varied from three to twelve-hops, with the number of coupled nodes varying from zero to the path length. Figure-3 depicts a representative sample of the results. In Figure-3 (a), the number of nodes is varied from three to twelve with no coupling between the two paths. The comparison of the simulated values to the asymptotic values shows that the analytical model is valid, but also demonstrates its limitations. Under light load the model provides tighter bounds for longer path length. For example, given a load of $\approx$ 25% the analytical model *over-estimate* maximum throughput by $\approx$ 150kbps. A curious, albeit, explainable result is that this effect reverses as the load approaches 50% and continues to increase– eventually reaching a state of constant backlog. Under these conditions the model is more precise for shorter paths. For a twelve-hop path the predicted upper-bound over-estimates throughput by nearly 50kbps, whereas, the bound appears precise for a three-hop path. Imprecision of the model under light load is due to queuing delay caused by "self-interference"(see Figure-1). It is interesting to note (see Table-3) that the delay decreases at each node as the input traffic process is smoothed to a rate that approaches the capacity of the system with self-interference. Hence, the effect is more pronounced for shorter paths. In contrast, at higher loads the major factor contributing to the queuing delay is the offered load. Self-interference becomes much less significant. Imprecision increases with path length because the model does not reflect the distribution of packet retransmissions which increase with load and hop-count.

Figure-3 (b) plots the relative throughput (throughput/load) logarithmically given a fixed six-hop path for three values of path coupling. The results are shown for both the analytical and simulation model. The comparative results are very close in all cases–six nodes coincidently shows excellent agreement between models under most scenarios for the given traffic distribution coupling patterns. The figure shows that the model predicts that paths will be able to sustain 100% throughput up to a load of 100kbps in all cases–this result is validated by the simulation. Without coupling the simulation validates that 100% throughput can be sustains to twice that load. However, both the single and dual coupled paths drop rapidly to 50% throughput at 200kbps.

In Figure-3 (b) simulation results show negligible difference between the single and dual coupled paths, whereas, the analytical model predicts significant difference. This can be attributed to a build-up in the first queue (the couplings proceed in according to the nodes position along the path) that acts to shape the traffic entering the second queue. Hence, the significant factor is the delay in the initial queue.



(a) Throughput versus load without path coupling

(b) Throughput versus ;pad with path coupling

Figure 3: Model Validation: Comparison of asymptotic results to simulation

The previous analysis suggests that the relative positions of couplings has a significant effect on system throughput. The simulated throughput in Figure-3 (b) is very close to the upper bound. This is because the two coupled nodes are only one hop away from each other. When delay is incurred at the first node due to coupling the second node is simultaneously affected by its own coupling (hidden-terminal). Hence, there is overlap in the busy time of these nodes; however, in analytical derivation the busy times are assumed independent. Consequently, the value of T_{obs} in the derivation is less precise. This special case shows that the position of couplings can affect the throughput of the network, suggesting utilization of a *position factor* in the throughput expressions.

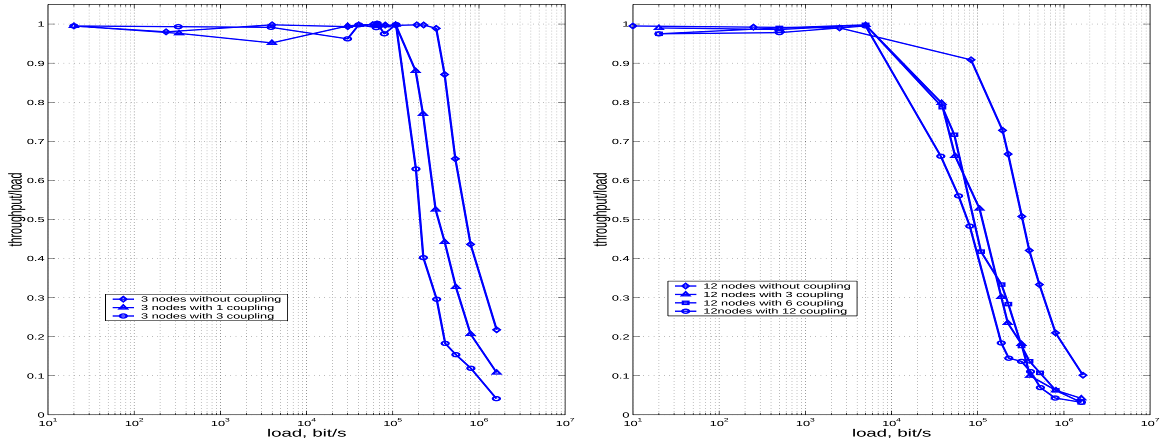
4.2 Analysis of Throughput and Power

Figure-4 demonstrates the dramatic effects of path coupling on capacity for three and twelve node path lengths. Each of the logarithmatic plots shows how increasing of the number of "linkages" through coupling effectively increases the contention for transmission bandwidth. Without coupling a twelve-hop path is shown to achieve $\approx$ 90% of throughput at 100kbps, dropping to $\approx$ 50% at 500kbps; whereas, a completely coupled path reduces the system throughput to $\approx$ 40% at only 100kbps. Figure-4 (b) shows that the system effectively collapses due to complete coupling at 10kbps—roughly 1% of the transmission capacity! These results agree with those in [11] under similar conditions. As expected the performance for the three-hop path is an order of magnitude better due to reduced contention and capacity for the network to "buffer" (or drop) packets.

The cross-layer interaction demonstrated by the results is harmful both with respect to system performance and analysis of higher-layer algorithms, e.g. routing, transport-layer, etc.. This observation should be disturbing based on the overwhelming presence of IEEE 802.11 in ad hoc network test-beds (using WaveLan radios, for example) and simulators including *ns2* and OPNET. [6],[8],[10]. In [14] it was pointed out that the "ad hoc" architecture supported by IEEE 802.11 **was not designed to support multihop ad hoc arrangements.**

The results expose a fundamental flaw in current ad hoc network design. The problem as demonstrated here and supported in [11], [14] is based on IEEE 802.11. However, the solution is not as simple as selecting another MAC protocol–wireless MAC algorithms must cope with hidden and exposed terminals, self-interference and efficient collision handling. Without control mechanisms the best throughput that can be expected is $\approx$ 36% form slotted-aloha, which is not acceptable. However, current control mechanisms are insufficient when traffic flows over paths with spacial proximity.

The question that arises is how to efficiently address this problem. Dynamic channel assignment has been proposed; however, it is difficult to achieve in practice as it reduces a dynamic graph coloring problem. Dynamic clustering [1], [12] with cluster-heads



(a) Three-hop paths

(b) Twelve-hop paths

Figure 4: System Throughput by degree of path coupling

acting as decentralized control agents have also been proposed as an effective means of controlling access to the transmission medium [7]. In [11] the authors suggest this is *the* fundamental limiting factor to ad hoc networking. The approach advocated here is to study how path selection process can be utilized to mitigate the problem. In effect the MAC layer and the routing algorithm should be jointly optimized and not be treated as separate entities.

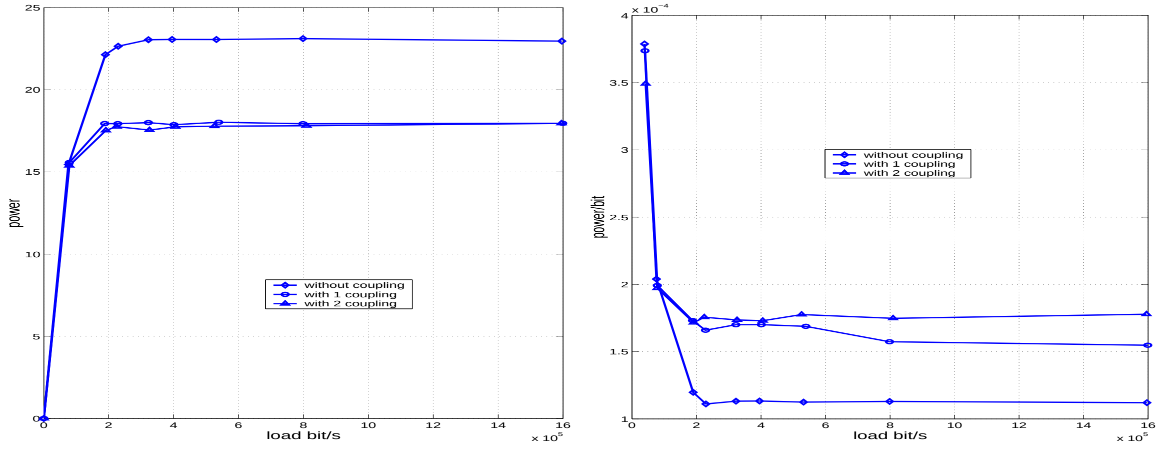
Figure-5 depicts two aspects of relative power consumption for a six-hop path (Figure-3 (b)) with zero, one and two coupled nodes. Figure-5 (a) plots the aggregate power consumption ratio relative to the *idle* state power versus offered load. Figure-5 (b) plots the relative power-per-bit (received) versus offered load. Observe in Figure-5 (a) that aggregate power consumption is a decreasing function of coupling. This is not counterintuitive, it is a direct result of the reduced throughput. Figure-5 (b) validates this assertion by showing that the power required to successfully transfer a bit from source to destination is an increasing function of coupling. Figure-6 and 7 (a) through (d) depict the distribution of the end-to-end delay, and the delays at specific nodes along a fixed six-hop path with zero coupling and two coupling respectively. Delay is defined as the difference of the time a packet enters the node until the node receives an ACK from the next hop. The corresponding statistics are shown in Table-3. As expected delay is increased through path coupling. In each case the queues act to shape the traffic, hence, the mean delay decreases at each hop along the paths. The most significant delays are shown to occur at the nodes where the coupling occurs. The surprising effect is that delays downstream of coupled links are less than the non-coupled counterparts. This suggests a strong correlation between delay and the positioning of the couplings in the paths.

statistics	0 couplings	2 couplings
Load	202.6kb/s	202.3kb/s
throughput	193.1kb/s	94.13kb/s
packets transmitted	630	296
mean delay at node 0	7226.6μs	16598μs
mean delay at node 1	2960.2μs	14357μs
mean delay at node 2	2099.9μs	2919.1μs
mean delay at node 3	1993.3μs	1785.4μs
mean delay at node 4	2126.1μs	2115.8μs
mean delay end to end	16424μs	38223μs

Table 3: Mean queuing delay at specific nodes

5 Conclusion

This paper examined the use of a contention based MAC layer protocol (IEEE 802.11) in ad hoc networks. Unlike previous research in this area the current paper approaches the problem as a cross-layer interaction that results in virtual coupling of network-layer paths. Both analytical and simulation models are de-



(a) Aggregate relative power consumption

(b) Relative power consumption per-bit

Figure 5: Power-ratio versus offered load

veloped that demonstrate the precise mechanism of the problem. The results agree in principle with previous work, however, the perspective taken is one of isolating the MAC-layer effects to understand them, and to use that understanding in future work to control the cross-layer interaction by developing routing metrics and cross-layer optimization methodologies that account for this important yet little studied problem.

References

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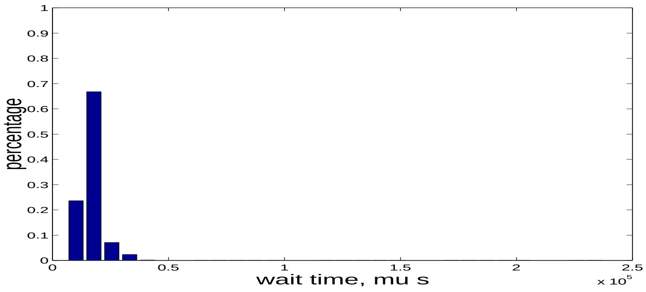
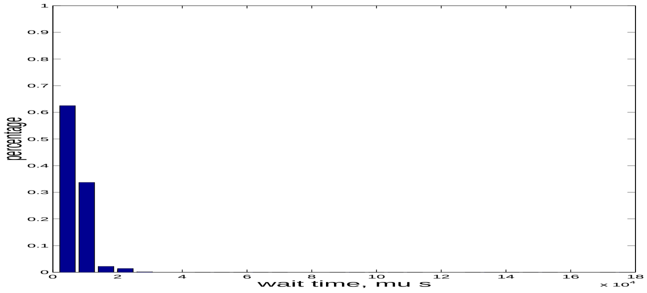
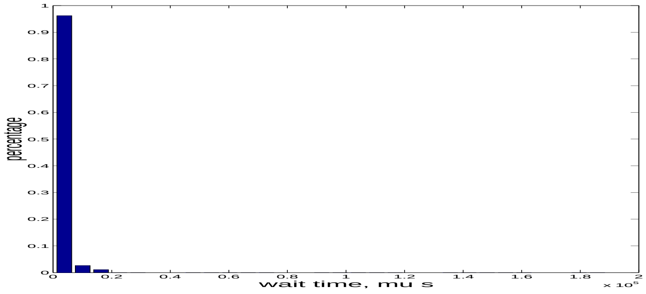


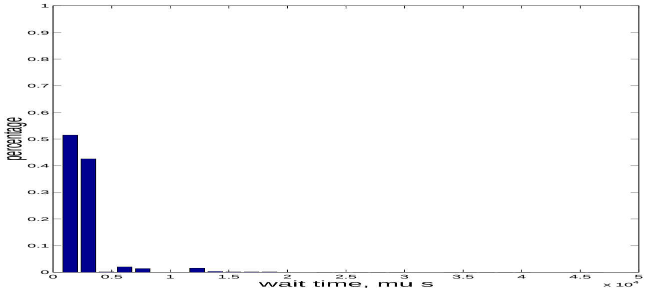
(a) Distribution of end-to-end delay



(b) Distribution of delay at node-0

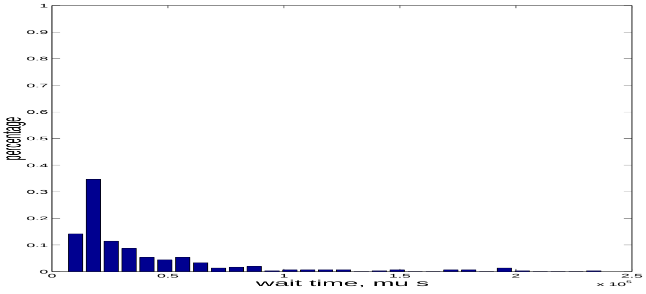


(c) Distribution of delay at node-1

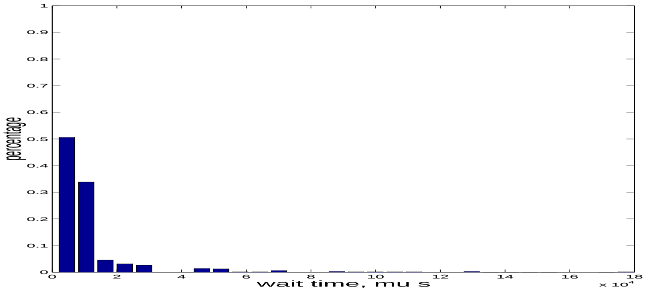


(d) Distribution of delay at node-2

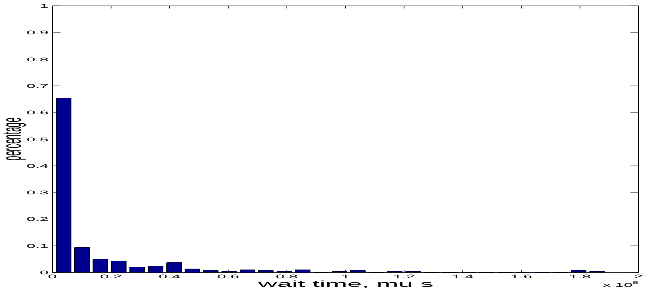
Figure 6: Distribution of end-to-end and node by node delay along a fixed path with zero coupled-linkages



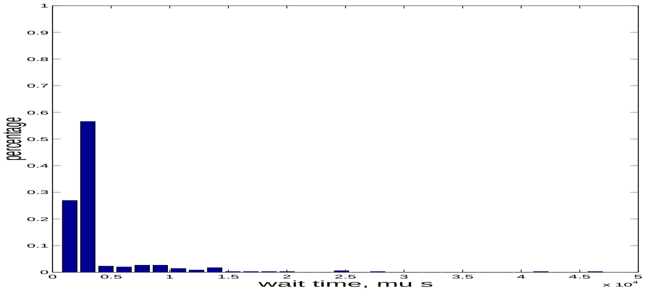
(a) Distribution of end-to-end delay



(b) Distribution of delay at node-0



(c) Distribution of delay at node-1



(d) Distribution of delay at node-2

Figure 7: Distribution of end-to-end and node by node delay along a fixed path with two coupled-linkages