# Harnessing the Parity of Multiple Errors in End-to-End MAC Schemes

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*Abstract*— **We present the results of simulation experiments that compare end-to-end error management (used in controlled access MAC protocols) against hop-by-hop error management (used in random access MAC protocols). Our experiments are novel in that we restrict both MAC schemes to identical power budgets and power distribution strategies. By making such a normalized comparison, we observe that end-to-end schemes are more effective than hop-by-hop schemes at reducing connection BER. We are also able to quantify the sensitivity of this relative advantage to various environmental parameters, including power budget size, geographic distance, the number of hops, and power distribution scheme.**

*Index Terms*— **wireless ad-hoc networks, MAC protocols, multi-hop path, lower bit error rate, Power budget, end-to-end error, hop-by-hop error.**

## I. Introduction

Wireless communication networks are being deployed at a tremendous rate, reshaping the way we live. For example, wireless ad-hoc networks combined with satellite data networks [6], [1], [16] are now able to provide global information services to users in remote locations that could not be previously reached by traditional wired networks. Advances in hardware technology are enabling explosive proliferation of new wireless communication devices to an growing user population.

Maximizing the potential of such trends requires the design of effective wireless communication protocols that are both energy efficient and packet loss resilient. Packet loss in wireless networks is due to various factors including signal fading, interference, multi-path effects, data packets collisions, etc [10], [4], [18], [20], [21], [5]. There are two well-known ways to achieve end-to-end reliability on multi-hop paths.

1) *Hop-By-Hop* schemes require the data link layer to detect errors at each hop of the path, and address such errors by retransmitting lost frames or by using forward error correcting codes.
2) *End-to-End* schemes assume data link layers are unreliable and retransmissions are performed end-to-end.

It is sometimes possible to consider a mixed strategy, where link layers perform a few retransmissions if necessary, but perfect reliability is only guaranteed through end-to-end mechanisms. Link layer technologies such as the 802.11 MAC protocol [15] adopt such a mixed approach, making a bounded number of retransmission attempts for each lost or corrupted frame. Further losses are then recovered through end-to-end retransmissions.

Regardless of where a scheme lies in the spectrum between Approach 1 and Approach 2, the ultimate measure of its efficacy must be its ability to support end-to-end reliable transfer. Indeed, as long as there is some link in the multi-hop path that can not guarantee reliable packet delivery, we must rely on TCP-like transport protocols to initiate end-to-end retransmissions by the source. This is true for several reasons, including:

- Link layer technologies such as IEEE 802.11 [15] implement a limited number of retransmissions, which results in possible delivery failure over lossy links.
- There are link level technologies that do not provide hop-by-hop retransmission (e.g. TRAMA [12]).
- Given link layer reliability, packet loss may still occur at network layer due to congestion [17].
- Nodes may move, sleep, or fail. In such cases, hop-by-hop reliability cannot be assumed, since even if a sleeping node can receive packets after waking up, the transport protocol may have timed out.

There are two categories of MAC layer protocols used in mobile ad hoc networks:

1) *Random Access* protocols require nodes to compete with each other to gain access to the shared wireless medium.
2) *Controlled Access* protocols utilize a master node to determine which node gets access to the wireless medium.

Random access protocols are a natural choice for medium access control in MANETs, because of their lack of fixed infrastructure. Examples of MAC random access protocols include Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA).

Controlled access protocols are preferred in environments that require Quality of Service (QoS) guarantees since node transmissions are collision free. QoS MAC protocols are an essential component in QoS support within MANETs. All upper layer QoS components including QoS routing and QoS signaling are dependent on the services of QoS MAC protocols operating at the data link layer. Large-scale MANETs are usually organized into clusters in order to minimize QoS routing traffic overhead and increase the network throughput.

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In such cluster-based MANETs it is natural to employ MAC controlled access techniques at the master nodes to coordinate access to the shared wireless medium. Examples of MAC controlled access protocols include Time Division Multiple Access (TDMA), Frequency Division Multiple Access (FDMA), and Code Division Multiple Access (CDMA).

Controlled access MAC protocols rely on end-to-end error detection, while random access MAC protocols perform hop-by-hop error detection. In controlled access MAC protocols, frames are redelivered only when the error detection mechanism fails to verify their correctness at the ultimate destination, while in random access MAC protocols, retransmission occurs at the hop where the error occurs.

*In this paper, we present the results of experiments that compare end-to-end error management (used in controlled access MAC protocols) against hop-by-hop error management (used in random access MAC protocols). Our experiments are novel in that we restrict both MAC schemes to identical power budgets and power allocation strategies. By making such a normalized comparison, we can observe that end-to-end schemes are more effective than hop-by-hop schemes at reducing connection BER. We are also able to quantify the sensitivity of this relative advantage to various environmental parameters, including power budget size, geographic distance, and the number of hops.*

The remainder of the paper is organized as follows. We begin in Section II by describing our formulation of hop-by-hop and end-to-end bit error rates for a wireless connection. In Section III we specify our network model and then in Section IV we describe the experimental setup under which the schemes are to be compared. In Section V, we present the experiment results and their analysis.

## II. Main Idea

Our approach relies on the following straightforward observation. A bit that experiences multiple errors during its transmission towards some destination is received in an error-free state if the number of error occurrences in transit is even; otherwise, the bit is received in an erroneous state. We propose that, somewhat paradoxically, the *parity of multiple errors* can be used reduce effective connection BER Rate.

Figure 1 shows a two hop transmission scenario of 5-bit long frame under an end-to-end MAC scheme. An error occurs in bits 1 and 5, on both links. In this example, the initial frame is received error-free despite the errors that occurred while traversing the intermediate hops. In general, an error is witnessed at the destination precisely when either link 1 or link 2 experiences an error (but not both). Thus, the total BER of the connection from node $s$ to node $t$ using this end-to-end MAC scheme is:

$$\begin{aligned} ber_{E2E} &= ber_1(1-ber_2)+ber_2(1-ber_1) \\ &= ber_1+ber_2-2ber_1ber_2. \end{aligned} \tag{1}$$

We now consider the same scenario under a hop-by-hop MAC scheme. An error is witnessed at the destination if no error occurs on either link. Thus, the total BER of the connection from node $s$ to node $t$ using this hop-by-hop MAC scheme is [1], [14], [19], [13]:

$$\begin{aligned} ber_{HbH} &= 1-(1-ber_1)(1-ber_2) \\ &= ber_1+ber_2-ber_1ber_2. \end{aligned} \tag{2}$$

Assuming that at least one of the two links has non-zero BER, it follows immediately that the end-to-end scheme achieves lower connection BER since

$$ber_{HbH} = ber_{E2E} + ber_1ber_2$$

and $ber_1ber_2 > 0$.

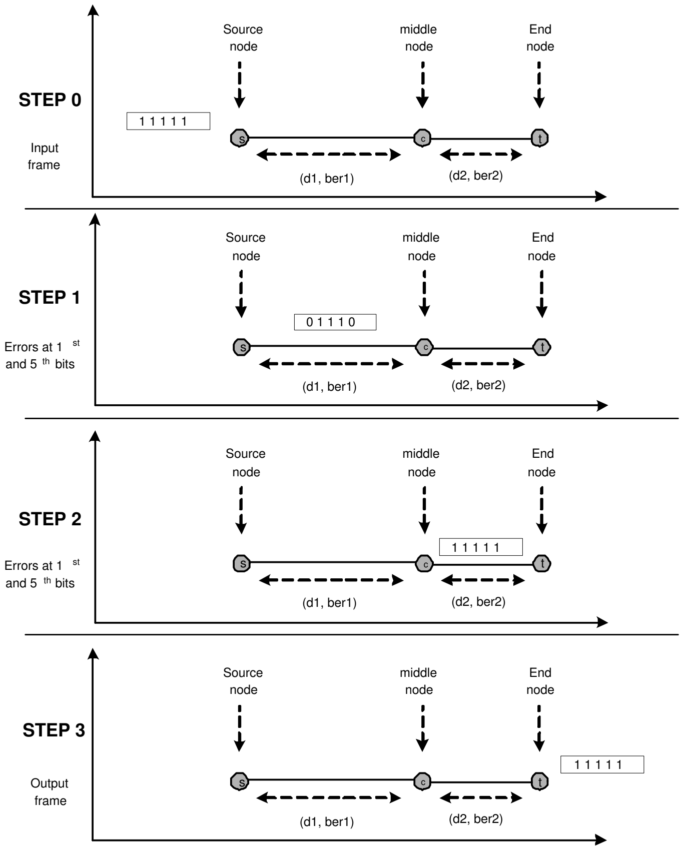


Fig. 1. End-to-end bit error rate case scenario

Expressions (1) and (2) are straightforward to generalize to connections consisting of more than two hops. Given a connection $C$ consisting of links $L_1, \ldots, L_r$, we define for each odd-cardinality subset $S \subset [1,r] = \{1,2,\ldots,r\}$:

$$p_{E2E}(S) = \prod_{i \in S} ber(L_i) \prod_{j \in [1,r] \setminus S} (1-ber(L_j))$$

while for each even-cardinality subset $S \subset [1,r]$ we take $p_{E2E}(S) = 0$. Since a bit error is witnessed at the destination precisely when the bit experiences an odd number of errors occur along the path, we get that:

$$ber_{E2E}(C) \;=\; \sum_{S\subset[1,r]} p_{E2E}(S). \tag{3}$$

In contrast, in a hop-by-hop MAC scheme, an error is witnessed at the destination if the bit experiences no error occurs on any link. Thus

$$ber_{HbH}(C) \;=\; 1-\prod(1-ber(L_i)). \tag{4}$$

The fact that $ber_{HbH}(C) \geqslant ber_{E2E}(C)$ is formally verifiable; here we present an intuitive argument. The quantity $ber_{HbH}(C)$ is the probability that at least one error occurs on the links $L_1,\ldots,L_r$, while the quantity $ber_{E2E}(C)$ is the probability that an odd number of links contribute to an error; every event measured by the latter expression is also measured by the former expression.

Having concluded that $ber_{HbH}(C) > ber_{E2E}(C)$, the following questions naturally arise: *How much better is the end-to-end scheme, and how is its relative advantage impacted by environmental parameters, including power budget size, geographic distance, and the number of hops?* In the next sections, we will address these questions through carefully conducted simulation experiments. To begin, we describe the wireless transmission model under which the experiments are conducted.

## III. Network Model

We consider, as in [2], [3], that a wireless ad-hoc network consists of $N$ nodes equipped with omni-directional antennas that can dynamically adjust their transmission power. We model this network as a linear geometric graph $G=(V,E)$, where $V$ is the set of nodes and $E$ is the set of edges. Each node is assigned a unique ID $i$ in $\{1,\ldots,|V|\}$, and node $i$ can send data with a dynamically tunable transmission power in the range $[0, P_{max}(i)]$.

Wireless propagation suffers severe attenuation [5], [14]. If node $i$ transmits with power $P$(i), the power of the signal received by node $j$ is given by

$$P_{rcv}(j)=\frac{P_t(i)}{c\times d_{ij}^{\alpha}}, \tag{5}$$

where $d_{ij}$ is the distance between nodes $i$ and $j$. $\alpha$ and $c$ are both constant, and usually $2\leqslant\alpha\leqslant 4$ (See [5]). In order to correctly decode the signal at the receiver side, it is required that $P(j)\geqslant\beta_0\times N_0$, where $\beta_0$ is the required signal to noise ratio (SNR) and $N_0$ is the strength of the ambient noise. We denote the minimum signal power at which a node is able to decode the received signal as $P_{min}$.

Each link $(i,j)$ has a computable bit error rate $BER(i,j)$, which represents the probability of the occurrence of an error during the data transfer over that link. The relationship between the bit error rate $BER$ over a wireless channel and the received power level $P_{rcv}$ is a function of the modulation scheme. It can be expressed in general as follows [5],

$$BER\;\propto\;Q\left(\sqrt{\frac{P_{\text{rcv}}Ct^e}{f\;P_{\text{noise}}}}\right), \tag{6}$$

where $P_{noise}$ is the noise spectral density, $f$ is the raw channel bit error rate, and $Q(x)$ is defined as follows.

$$Q(x)=1-\frac{2}{\pi}\int_0^x e^{-t^2}\,dt. \tag{7}$$

Since we are only interested in studying the general dependence of the bit error rate on the received signal power, we will consider the non coherent binary orthogonal Frequency Shift Keying (FSK) modulation scheme. Other modulation schemes can be analyzed in similar way, however closed-form analysis may not be always possible. For this specific modulation scheme, the instantaneous channel bit error rate $BER$ is given by [9], [11], [8] to be:

$$BER=\frac{1}{2}\,e^{-\frac{P_{\text{rcv}}}{2P_{\text{noise}}}} \tag{8}$$

## IV. Experimental Setup

In our simulations, we consider connections spanning both short and long multi-hop paths. The intermediate nodes were randomly distributed between two endpoints situated at a distance which varied between $100m$ and $400m$. We consider both small and large power budgets $P$ that were distributed among the intermediate nodes of the multi-hop path using one of three schemes. More precisely, all experiment parameters were kept in the following ranges:

- *Path Length*: We consider path lengths ranging from short (5 intermediate nodes) to long (25 intermediate nodes).
- *Power budget*: We consider connection power budgets ranging from small (1 Watt) to large (10 Watts).
- *Distance*: We consider scenarios in which the two endpoints range from nearby ($50m$) to distant ($300m$).
- $\alpha$: A scaling constant is kept fixed at 2, as appropriate to our connection scales.
- $SNR$: The Signal to Noise Ratio of the wireless channel is kept fixed at 1mW, as appropriate to a typical $SNR$ value for wireless channel.

The following power distribution schemes were used to distribute the power budget to intermediate nodes along the connection path.

- *Uniform*: Given a connection between nodes $s$ and $t$ with length $k{+}1$ hops and a total power budget $P$. The uniform power distribution scheme consists of allocating to each of the $k$ nodes (excluding the destination node) a uniform fraction of the total power $P_{unif}=\frac{P}{k}$.
- *Sqr*: Under this power distribution scheme, the power is allocated based on the square of the distance to the next hop along the path towards the destination node. Specifically, given a connection between nodes $s$ and $t$

with length $N-1$ hops and a total power budget $P$, each node $j$ will be allocated a power $P_{sqr}$ such that $P_{sqr} = Pd_j^2 / \sum_{i=1}^{N-1} d_i^2$, where $d_j$ is the distance from node $j$ to node $j+1$ along the path.

- *Dynamic*: This scheme assumes that power is distributed among intermediate nodes in a manner that satisfies the following local optimality condition: Each non-endpoint node, considered as the *central node* in the subpath of length two connecting its upstream and downstream neighbors, believes that the power is distributed between it and its upstream neighbor in a way that provides optimal BER for the two-hop path (Figure 2). More details about this power distribution scheme are provided in [7].

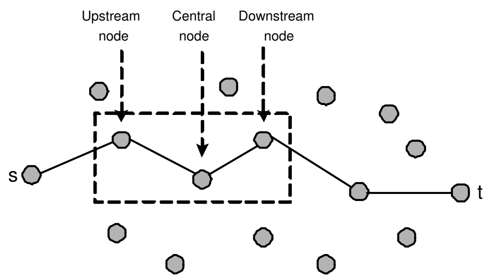


Fig. 2. Local Optimality Condition

The graphs in the next section depict average values collected from $10^4$ trial runs for each experiment scenario. In our experiment, we compared the end-to-end and the hop-by-hop MAC schemes under various power budgets, path lengths, endpoint distance scales, and power distribution schemes.

## V. Results and Analysis

In this work, we conducted extensive simulation experiments to study the end-to-end Bit Error Rate (BER) in MANETs using random access as well as controlled access techniques. Our simulation results show that the end-to-end BER in MANETs that use controlled access MAC protocols is significantly less than the end-to-end BER obtained when using random access MAC protocols.

We compare the performance of our *end-to-end* (E2E) MAC schemes with *hop-by-hop* (HbH) MAC schemes. For each of these schemes, we study the impact of varying the path lengths, connection power budgets, endpoint distance, and power allocation scheme. The legends of each curve indicate the average relative performance of two schemes. For example in Figure 3, the curve titled *Uniform E2E/HbH* shows the average value of the quantity

$$\frac{BER_{HbH} - BER_{E2E}}{BER_{HbH}}.$$

The fact that this curve passes through the point $(100m, 40\%)$ indicates that when the distance between the endpoints was

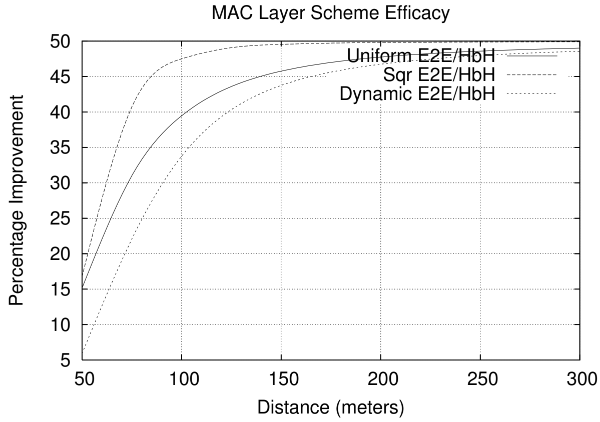


Fig. 3. Percentage improvement vs. total connection distance

100m, the BER achieved by *E2E* scheme was (on average) $40\%$ lower than what was achieved by *HbH* scheme, over the $10^4$ random trials conducted using Uniform power distribution strategy.

Figure 3 illustrates the impact of varying the distance between the connection endpoints, while keeping constant both the number of intermediate hops and the total power budget. The connection power budget was fixed at $2200mW$, and the number of intermediate nodes was fixed at 10—thus the average node transmission power was approximately $220mW$, in the range of present $54$Mb/s wireless technology. Considering the *asymptotes* of these curves we conclude that the improvement of the *E2E* scheme relative to the *HbH* schemes converges to $50\%$, as the distance between endpoints increases. The improvement attained by using *E2E* MAC was most dramatic for the *Sqr* distribution scheme, and least effective for the *Dynamic* scheme, with the *Uniform* scheme deriving intermediate benefit from the choice of MAC error management strategy.

Figure 4 illustrates the impact of the power budget on the performance of each power allocation scheme. The distance between endpoints was fixed at $120m$, and the number of intermediate nodes was fixed at 9—thus the average internode spacing was approximately $12m$, in the range of present $54$Mb/s wireless technology. Considering the *asymptotes* of these curves we conclude that the improvement of the *E2E* scheme relative to the *HbH* schemes converges to $0\%$, as the power budget increases. The decline in improvement is sharpest for the *Dynamic* distribution scheme, and slowest for the *Sqr* scheme, with the *Uniform* scheme deriving intermediate benefit from the choice of MAC error management strategy.

Figure 5 illustrates the impact of varying the path length (in terms of the number of intermediate nodes) between the source and destination nodes while keeping constant both the distance between the connection endpoints and the total power budget. The connection power budget was fixed at $2200mW$, and the number of distance was fixed at $120m$–

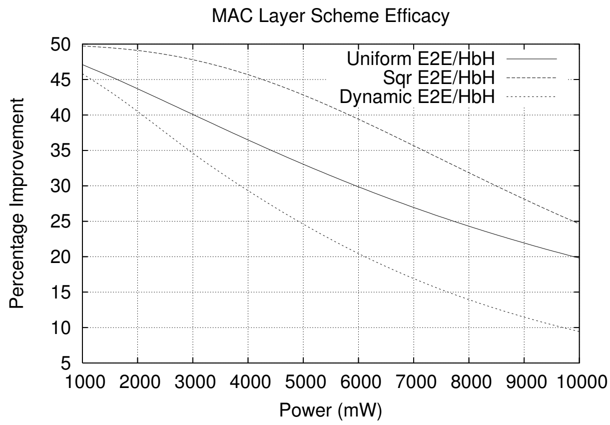


Fig. 4. Percentage improvement vs. total connection power budget

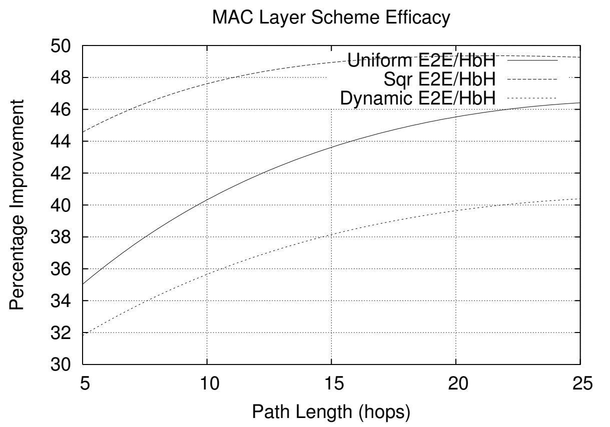


Fig. 5. Percentage improvement vs. path length

drawing upon the two experiment scenarios described earlier. Considering the *asymptotes* of these curves we conclude that the improvement of the *E2E* scheme relative to the *HbH* schemes converges to a plateau value, ranging from $41$ to $50\%$. The *Sqr* scheme derives the greatest benefit from the *E2E* MAC, while the *Dynamic* scheme derives the least benefit. The *Uniform* scheme consistently derives intermediate benefit from the choice of MAC error management strategy.

## VI. Conclusion

The results of our simulation experiments validate the theoretical ideas derived from our initial, somewhat paradoxic observation, the *parity of multiple errors* can be used to reduce the effective connection BER Rate. Our comparison of end-to-end error management (used in controlled access MAC protocols) against hop-by-hop error management (used in random access MAC protocols) were conducted in a setting in which both schemes were subject to identical power budgets and power distribution strategies. In all scenarios, end-to-end schemes attained lower BER than hop-by-hop schemes. In making such a normalized comparison, we were able to quantify the sensitivity of this relative advantage to various environmental parameters. We found that the advantage of end-to-end schemes is maximized in settings where the power budget is small, the endpoint separation is high, or the number of intermediate hops is high. The *Sqr* power distribution scheme consistently derives the greatest benefit from *E2E* MAC, while the *Dynamic* scheme derives the least benefit.

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