Effects of Unintentional Denial of Service (DOS) Due to Push-to-Talk (PTT) Delays on Performance of CSMA/CA Based Adhoc Land Mobile Radio (LMR) Networks

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Abstract. Unintentional Denial of Service (DOS) problems occur in wireless networks such as Wi-Fi due to factors such as signal capture, interference and have been studied extensively in the literature. A similar problem manifests amongst nodes within a LMR network due to different PTT delay characteristics. We first present the typical PTT delay values and distributions followed by an analytical model to estimate the denial of service problem. The results obtained using the model and simulations show that the LMR nodes experience DOS due to collisions resulting from PTT delays. The results also show that there exists an asymmetry in the performance of individual nodes and the extent of this asymmetry is a function of total number of nodes in the system and the density of nodes with similar PTT delay profiles. These observations have implications in both performance and capacity planning of an adhoc LMR network.

Keywords: Denial of Service, PTT delays, CSMA, Adhoc, Land Mobile Radio.

1 Introduction

The number of wireless devices has increased exponentially over the past decade. Wireless networks today exist in a variety form factors, from Metropolitan Area Networks (MAN) like 802.16 (WiMAX), HiperLAN/2 to Personal Area Networks (PANS) like 802.15 (ZigBee) and are used in a wide range of applications like cellular networks and RFIDs. In addition to these next generation networks, attempts are also being made to integrate the legacy networks like Land Mobile Radio (LMR) into the internet backbone making the internet truly ubiquitous [1],[2],[3].

Traditionally, the use of LMR networks was restricted to that of transmitting voice signals in various Public Safety and Law Enforcement, Emergency Medical Services (EMS) and Military applications. However over the past few decades, digital radio based LMR networks like TETRA and APCOs P-25 have incorporated data communication along with voice transmission. The Digital Distributed Radios (DDR) proposed in [4] provides a low-cost IP-based connectivity using convention analog LMRs. These technologies have enabled the next generation digital LMR nodes to

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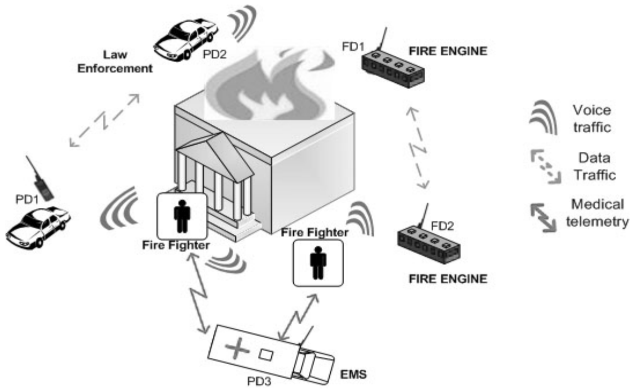

Fig. 1. Adhoc network based on digital LMR technology

communicate critical data like physiological status of first responders, location information and environment data in addition to voice. A typical implementation of an adhoc LMR network is shown in Figure 1 [1].

One of the factors affecting the throughput of an adhoc network is the performance of Medium Access (MAC) layer protocol like Carrier Sense Multiple Access (CSMA) [5]. The performance of CSMA depends on the probability of collision and channel utilization amongst nodes and has been extensively studied in literature. There are a number of analytical models which correlate the performance of CSMA protocol to MAC-layer factors like backoff algorithm and schedule pipelining [6],[7]. Performances due to capture effect, propagation delays and directional antennas have also been studied for WLAN networks [8],[9]. A multi-node adhoc WLAN is also prone to an asymmetric throughput problem arising due to several factors like unfair access [10] or Unintentional Denial of Service (DOS) attacks [11]. For LMR networks, in addition to the aforementioned factors, another important parameter that can affect the throughput is a Push-To-Talk (PTT) delay. A PTT delay refers to the delay between the instant when PTT line (switch), on a conventional LMR radio, is keyed/unkeyed and the instant when a response is observed at the radio output. These delays result in an increase of the collision window size. Typical PTT delay values for LMR terminals can run between tens to hundreds of milliseconds [12],[13],[14]. Since the use of LMR networks was traditionally restricted to voice traffic, in which a user himself provided the mechanism for channel access, the effects of PTT delays has been greatly overlooked in literature. Most of the collision analysis found in literature accounts for collision probability depending upon the contention interval. In these cases the collision window is limited to few a microseconds corresponding to propagation delays. Since PTT delays can protract this collision window to several hundreds of milliseconds, the study of PTT delays and their influence on network performance warrants investigation.

In this paper, we highlight the unintentional denial of service problem observed in an adhoc LMR network. In Section 2 we present the PTT delay values and distributions observed for two of the commonly used LMRs. Section 3 introduces the MAC layer implementation under consideration followed by an analytical model for probability of collision which leads to a DOS for each node in Section 4. Section 5 presents the results of simulations and conclusions are provided in Section 6.

2 Push-To-Talk (PTT) Delays

As mentioned in Section 1, PTT delay refers to the time difference between the instant when PTT line (switch), on a conventional analog radio is keyed and the instant when a RF carrier is observed at the antenna output. This delay is referred to as Receive-To-Transmit Switch Interval (RTSI). A similar delay occurs when the PTT line is un-keyed and is referred to as Transmit-To-Receive Switch Interval (TRSI). These delays occur due to the latency involved in switching between transmit and receive

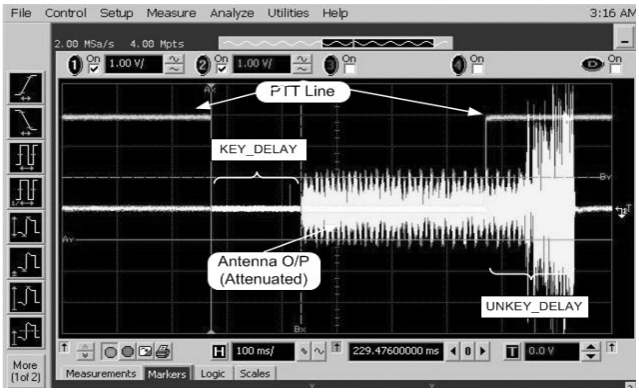

Fig. 2. Delay during keying (RTSI) and un-keying (TRSI) for a conventional analog radio

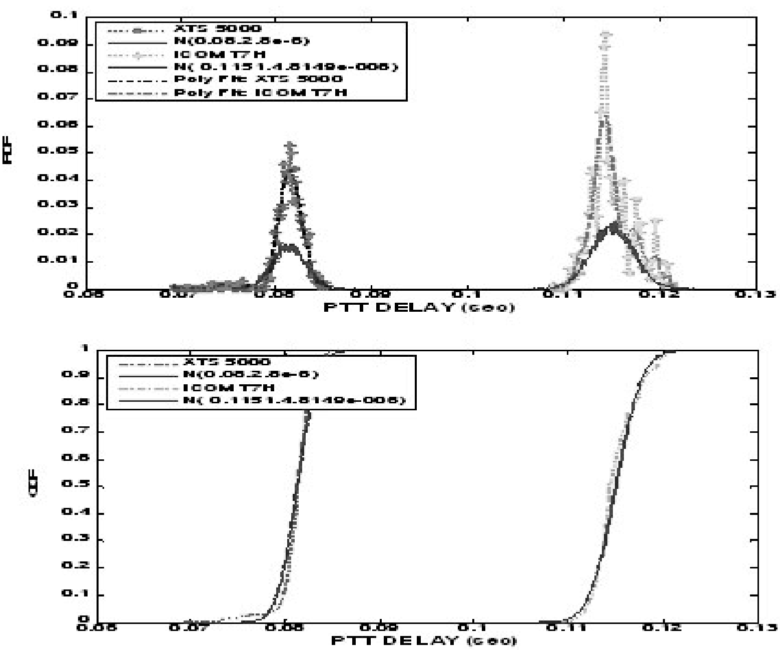

Fig. 3. Distribution of RTSI delays for Motorola XTS 5000 and ICOM IC-T7H

hardware chains. The PTT delay profile for a LMR radio is shown in Figure 2. In this paper we will focus on RTSI delays alone. Figure 3 shows the PTT Delay distribution observed for a Motorola XTS 5000 and ICOM IC-T7H radio sets [13], [14].

From Figure 3a, we observe that the mean value of RTSI delay for a Motorola XTS 5000 radio was approximately 83 msec and that for the ICOM IC-T7H radio was approximately 114 msec. The Gaussian distribution and polynomial fit for PTT delay values for Motorola XTS 5000 and ICOM IC-T7H can be seen in Figure 3a. It can be observed that the 3rd degree polynomial fit approximates the PTT delays with better fidelity than a Gaussian distribution fit. The Cumulative Distribution Function (cdf) for the RTSI delay values is shown in Figure 3b.

3 CSMA/CA Implementation for the Medium Access Layer (MAC)

The MAC layer implementation ensures fair access to a shared resource such as a wireless channel. As discussed before, for voice transmissions, the users themselves enforce a de-facto contention resolution mechanism. For data transmissions some variation of channel access mechanisms like Time Division Multiple Access (TDMA)/Frequency Division Multiple Access (FDMA)/ CSMA, is used [5]. CSMA is a classic protocol used to arbitrate channel access between contending nodes in WLANs. CSMA can be implemented as a non-persistent or p-persistent protocol. Modified versions of CSMA protocols such as CSMA with Collision Avoidance (CSMA/CA) [15], Floor Acquisition Multiple Access (FAMA) [16], Multiple Access with Collision Avoidance (MACA) [17], provide collision avoidance by using a preamble or extensive handshaking procedures.

For our current analysis, we consider a variation of p-persistent CSMA/CA protocol [5],[15]. Any radio which has a packet to send first senses the channel to detect any existing transmissions. If the channel is occupied, the packet is identified as backlogged and queued for retransmission. The CSMA protocol is designed to reduce collision probability between multiple LMR nodes, at the point where collisions will most likely occur. Just after the channel becomes idle (as detected by carrier sensing) is when the highest probability of collision exists. This is because multiple nodes might be waiting to transmit data. To avoid collisions, each LMR node which has a backlogged packet selects a random backoff before initiating data transfer. The backoff time is selected randomly within a uniformly distributed backoff time window. The length of the window, which defines the contention interval, depends on the backoff scheme implemented. Thus each LMR node with a backlogged packet transmits packets with a probability p the next time channel becomes free [5].

4 Unintentional Denial of Service (DOS) Due to RTSI Delays

From Figure 2, it can be inferred that PTT delays will affect the performance of CSMA/CA algorithm since any decision about the channel availability during RTSI will yield erroneous results. For a node which has elected to transmit, the carrier sensing mechanism will be suspended during RTSI interval. Conversely, other LMR nodes sensing the channel during this RTSI, will infer that the channel is free for

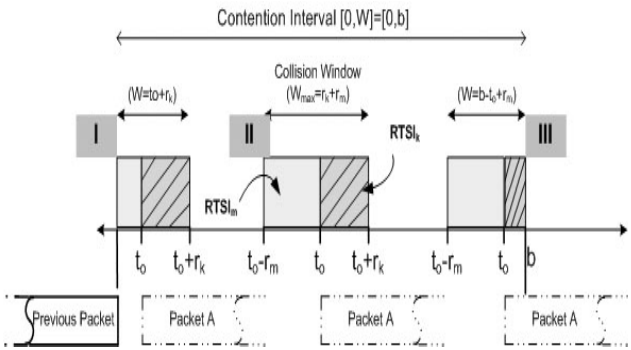

Fig. 4. Collision window for a single node

transmission and may commit to packet transfers. Thus RTSI increases the collision window between contending LMR nodes, increasing the probability of collision. Figure 4 delineates the impact of RTSI on collision window size. A collision within the duration of a collision window can be interpreted as an unintentional interference and will result in a denial of service for the transmitting node.

To better understand the impact of an increase in collision window size, consider an adhoc LMR network consisting of two nodes with RTSI delays of r_k and r_m seconds ($r_m > r_k$). The size of contention interval, which refers to the window within which a node selects a uniformly distributed time instant to transmit a packet, depends upon the backoff algorithm implemented. For simplicity in analysis, assume a memoryless channel access i.e each node will attempt to access the channel irrespective of the outcome of the previous attempt. This means that the backoff interval is fixed. Under these assumption the contention interval can be assumed to be constant [0,b].

In absence of RTSI, the collision window would normally extend to few micro seconds corresponding to the propagation delays. However in presence of RTSI, the protracted collision window can be recomputed as

$$W = \begin{matrix} r_k + r_m\,; & r_m \le t_0 \le (b - r_k) \\ t_0 + r_k\,; & t_0 < r_m \\ b - t_0 + r_m\,; & t_0 > (b - r_k) \end{matrix} \tag{1}$$

where t_0 represents the time instant when a node decides to transmit data packet. Since the value of RTSI is in order of tens of milliseconds as compared to microseconds associated with propagation delays, we can ignore the impact of propagation delay on collision window size. Assume that Node K decides to transmit at an instant t_0. Due to RTSI, other nodes in the network will sense the channel activity only after t_0+r_k seconds. Thus it is possible for any other node which is scheduled to transmit packet between the interval $\{t_0, t_0+r_k\}$ to sense the channel inactive and hence commit to a transmit. This will result in collision between the two or more transmitting nodes. This length of the collision window is represented by $RTSI_k$ in Figure 4. The same argument is applicable to the original transmitting node i.e. while making a decision about the activeness of the channel, it cannot be sure that no other node has already committed to transmit within the interval $\{t_0\text{-}r_m, t_0\}$. This is shown in Figure 4 as

$RTSI_m$. Thus the competing nodes can unintentionally collide with each other resulting in an unintentional DOS for the transmitting node.

In order to derive an expression for the conditional probabilities of collision we can use the probability distribution diagram shown in Figure 5. The random variable y represent the time instant of transmission for node m (t_m), while random variable x represents the time instant of transmission for node k (t_k). We also assume saturated load conditions i.e every node in the network always has packets to transmit.

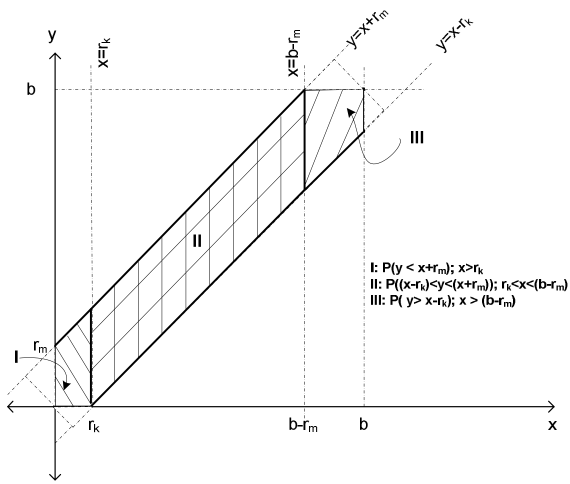

Fig. 5. Probability of collision between two nodes with different RTSI delays

From Figure 5, we can calculate the conditional probability of collision for both node m and node k as

$$P\left(C/t_k=\tau\right)=P_{mk}$$
$$=\begin{cases} P((\tau-r_m)\le t_m\le(\tau+r_k)); & r_m\le\tau\le(b-r_k) \\ P(t_m<(\tau+r_k)); & \tau<r_m \\ P(t_m>(\tau-r_m)); & \tau>(b-r_k) \end{cases} \tag{2}$$
$$P\left(C/t_m=\tau\right)=P_{km}$$
$$=\begin{cases} P((\tau-r_k)\le t_k\le(\tau+r_m)); & r_k\le\tau\le(b-r_m) \\ P(t_k<(\tau+r_m)); & \tau<r_k \\ P(t_k>(\tau-r_k)); & \tau>(b-r_m) \end{cases}$$

Equation (2) can be extended to a network consisting of a total of N nodes out of which K nodes have RTSI delay of r_k and M nodes have RTSI delay of r_m. Under these conditions, we can derive a closed form expression for the conditional probability of collision for each node over an N node heterogeneous network as shown below.

$$
\begin{aligned}
P(C/t_k = \tau) &= 1 - \{\Pr(no\,nodes \quad collide)\} \\
&= 1 - \{(1 - (F_t(\tau + r_k) - F_t(\tau - r_k) \\
&\quad - 2F_t(r_k)))^{(K-1)} * \\
&\quad (1 - (F_t(\tau + r_k) - F_t(\tau - r_m) - F_t(r_m) \\
&\quad - F_t(r_k)))^{M}\}
\end{aligned} \tag{3}
$$

$$
\begin{aligned}
P(C/t_m = \tau) &= 1 - \{\Pr(no\,nodes \quad collide)\} \\
&= 1 - \{(1 - (F_t(\tau + r_m) - F_t(\tau - r_k) \\
&\quad - F_t(r_k) - F_t(r_m)))^{K} * \\
&\quad (1 - (F_t(\tau + r_m) - F_t(\tau - r_m) - \\
&\quad 2F_t(r_m)))^{(M-1)}\}
\end{aligned}
$$

From the above equation, the average value of collision window for the two node types can be approximated as

$$
\begin{aligned}
W_{Mavg} &= E[W_m] \approx [K(r_k + r_m) + (M-1)(2r_m)]/N \\
W_{Kavg} &= E[W_k] \approx [(K-1)(2r_k) + M(r_k + r_m)]/N
\end{aligned} \tag{4}
$$

Figure 6 shows the normalized collision window (W_{Mavg}/W_{Kavg}) size for a node m and node k for various adhoc LMR network configurations as a function of different RTSI

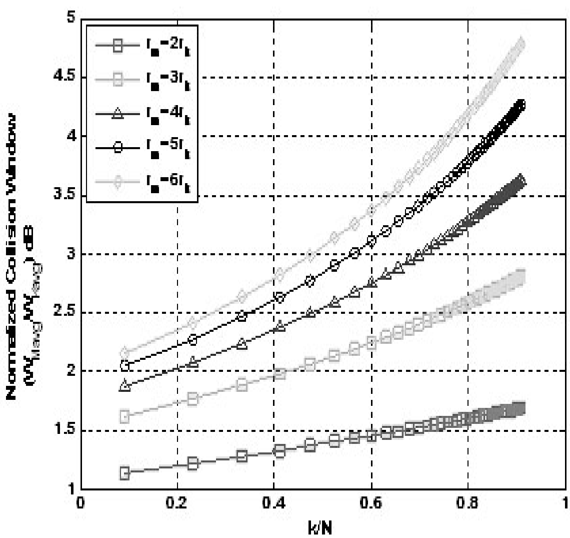

Fig. 6. Difference in the collision window sizes between m nodes and k nodes

delays. We can see that the average value of collision window (W_{Mavg}) for the node type m which has a higher RTSI value, r_m is higher than that for the node (W_{Kavg}) type k which has a lower RTSI value, r_k.

In addition to the relation between the two RTSI values, the normalized collision window size also depends upon the number of k type nodes in the N node network. As the number of k type nodes increases, the ratio of W_{Mavg}/W_{Kavg} also increases. Furthermore, the rate of increase in this ratio is also dependent upon the difference between the values of RTSI delays. From (3) and (4), it can also be concluded that greater the size of collision window, higher is the risk of unintentional denial of service due to collisions with other nodes. Thus nodes with larger RTSI delays (m-type in this case) will incur a higher probability of collision as compared to that of nodes with lower RTSI delays (n-type in this case). Alternatively, nodes with lower RTSI delays will have a greater probability of successful transmissions. This leads to an asymmetry in the number of DOS seen by individual nodes in the same network.

Equations (3) and (4) can be further extended to a generic N-node adhoc LMR network which consists of $p_1, p_2 \ldots p_n$ n-types of nodes with RTSI delays of $r_1, r_2 \ldots r_n$ msecs and a population of $s_1, s_2 \ldots s_n$ nodes respectively ($s_1+s_2+..+s_n=N$). The conditional probability of collision and the size of collision window for a node p_i in such a network can be computed as shown below

$$\begin{aligned} P(C/t_i = \tau) &= 1-\{\Pr(no\,nodes \quad collide)\} \\ &= 1-\{(1-(F_t(\tau+r_i)-F_t(\tau-r_i) \\ &\quad -2F_t(r_i)))^{(s_i-1)} * \\ &\quad \prod_{\substack{j=1 \\ j\neq i}}^{n-1}(1-[(F_t(\tau+r_i)-F_t(\tau-r_j) \\ &\quad -F_t(r_j))-F_t(r_i)])^{s_j}\} \end{aligned} \tag{5}$$

$$W_{iavg} = 1/N\,[(s_i-1)(2r_i)+\sum_{\substack{j=1 \\ j\neq i}}^{n-1}(s_j)(r_j+r_i)]$$

5 Simulation

Equation (3) gives a closed form expression for computing the conditional probability of collision for an individual node in a N-node heterogeneous network in terms of the probability distribution function F_t. It can be further extended to include more than two RTSI profiles as shown in (5). Form the objective of highlighting the effects of RTSI delays, two types of nodes (k,m) with different RTSI values (r_k,r_m) will be considered for simulations. Matlab is used to simulate a network of N nodes. In order to compute the conditional probabilities in (3), let us assume that the random variable t_i which represents the instant of transmission is uniformly distributed. Let the backoff window and hence the contention interval is fixed. The contention interval (0,b) is assumed to be of length 32*max(r_k,r_m) which is the minimum value of contention window in 802.11 standard [18]. Also assume that the RTSI values associated with two node types are constant values represented by r_k =80 msec and r_m=110 msec. Under these assumptions, Equation (3) can be re-written as shown below

$$\begin{aligned}
P(C/t_k = \tau) &= 1 - \{\Pr(no\ nodes \quad collide)\} \\
&= 1 - \{(1 - 1/b^2((b - r_k - r_k)(r_k + r_k) \\
&\quad + 3(r_k r_k))^{(K-1)} * \\
&\quad (1 - 1/b^2((b - r_m - r_k)(r_m + r_k) \\
&\quad + 1/2(r_k r_k) + 2(r_k r_m) + 1/2(r_m r_m))^{(M)}\}
\end{aligned} \quad (6)$$

$$\begin{aligned}
P(C/t_m = \tau) &= 1 - \{\Pr(no\ nodes \quad collide)\} \\
&= 1 - \{(1 - 1/b^2((b - r_m - r_m)(r_m + r_m) \\
&\quad + 3(r_m r_m))^{(M-1)} * \\
&\quad (1 - 1/b^2((b - r_k - r_m)(r_k + r_m) \\
&\quad + 1/2(r_k r_k) + 2(r_k r_m) + 1/2(r_m r_m))^{(K)}\}
\end{aligned}$$

Figure 7 and Figure 8, show the difference in conditional probability of collision for a *k* type node and a *m* type node using simulations and the analytical model given by (3) and (6). The simulation results validate the analytical equation. Form the figures it can be further inferred that the difference in conditional probabilities is a

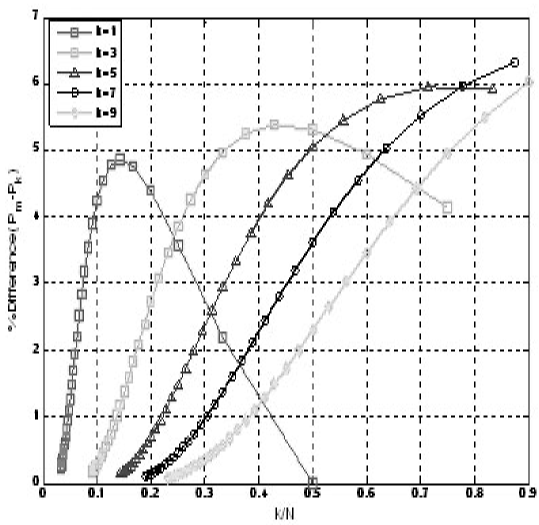

Fig. 7. Theoretical Difference in the probability of collisions between *m* nodes and *k* nodes

function of both the number of faster nodes in the network and also the size of the total network. For the constant ratio between faster nodes to slower nodes, the difference in collision probabilities depends upon the total number of nodes. Greater the total number of nodes, we need a higher ratio between faster nodes and slower nodes to get the maximum asymmetry between individual DOS.

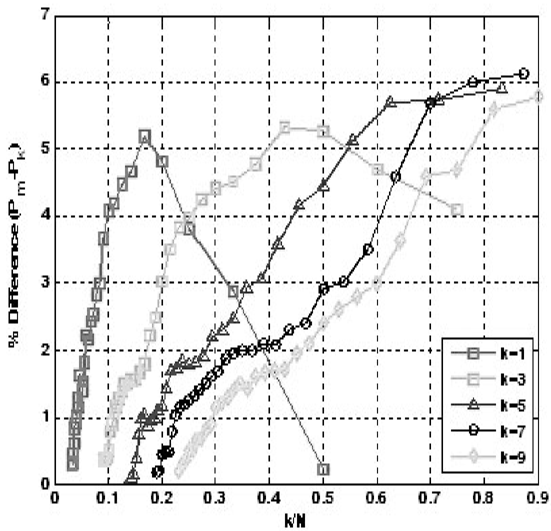

Fig. 8. Simulated Difference in the probability of collisions between m nodes and k nodes

7 Conclusions

In this paper, we developed an analytical model to highlight the unintentional denial of service problem due to Push-To-Talk (PTT) in CSMA\CA based adhoc Land Mobile Radio (LMR) networks. A similar analysis can be extended to other variations of CSMA protocol. The PTT delays discussed in this paper can be separated into two parts RTSI and TRSI. RTSI delays lead to an increase in collision window size. This increases the number of DOS events as the individual nodes in the network collide with each other more frequently. In addition to decreasing the total network throughput, this also results in an asymmetric performance amongst different radios depending upon their individual RTSI profile. The radios with lower RTSI delays will observe a lower DOS and hence a increased probability in successful transmissions as compared to radios with higher RTSI delays. These observations can prove useful during capacity planning for LMR networks since the probability of collision observed by nodes may change depending upon the PTT delay profile of the radios. One of the ways to solve this problem would be by using discreet-sized backoff intervals which account for RTSI delays. This approach will be able to decrease number of collisions, but may result in lowering of network throughput. Future publications will present results on the tradeoff.

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