Starvation effect study in IEEE 802.11 mesh networks

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***Abstract*—Initially, IEEE 802.11 standard was not designed for multihop networks, but its market success gave it a powerful incentive, and nowadays IEEE 802.11 Working Group is preparing various amendments and looking for new application scenarios to ensure future success in the market. In this paper, we analyze the performance of an IEEE 802.11s mesh network and show that the effect of starvation caused by hidden terminals interference makes the distribution of channel capacity between links very much disproportional and unpredictable. Some links may be suppressed completely by other links and their throughput is close to zero.**

The effect of starvation was discovered by simulations in many papers. We investigate the roots of this phenomenon in a mesh network with an analytical model. Also, this paper reports the results of an outdoor testbed which was deployed to find out the scale of the starvation problem in a real network with Voice-over-IP, Video-over-IP and FTP traffic. While the results for VoIP may be considered as satisfactory, FTP traffic suffers dramatically from interference. So, at the end of the paper, we outline possible solutions to address starvation problem in mesh networks.

***Index Terms*—IEEE 802.11; starvation effect; mesh; hidden terminal; interference**

I. Introduction

Two "classical" topologies of IEEE 802.11 [1] networks – ad hoc and infrastructure – have been extensively studied for many year with analytical and simulation models. Thousands of papers were written on performance evaluation of, it would seem, all mechanisms of these networks. But new alternative topologies as well as modifications to the existing topologies are now appearing on the horizon and it is still to be fully understood what challenges these new topologies have to face and how other mechanisms will evolve to support these topologies efficiently.

IEEE 802.11 Task Group "z" is developing an amendment that enables direct link connectivity between end stations, thereby avoiding unnecessary transmissions to and from an Access Point (AP). In turn, Task Group "s" is developing an amendment that enables mesh networking implying dynamic self-organization, self-configuration, self-healing and, in the first place, direct transmission between mesh stations in the absence of any base station. Both "z" and "s" networks support direct transmissions and multihop neighborhood.

In the networks with direct connectivity between stations, channel access method is the first candidate to be re-evaluated, because its performance is dramatically affected by direct transmissions. One may think that channel access method efficiency in a mesh network is the same as that in an ad hoc network where stations exchange frames directly too, but this is incorrect because a mesh is a multihop network, so hidden terminals affect its performance badly. One may say that an infrastructure network may also be a two-hop network and RTS/CTS handshake helps to limit the damage caused by hidden terminals, but the AP in the infrastructure network is the only station replying to RTS frames sent by other stations, which is the only reason why RTS/CTS handshake is useful to avoid links starvation, as shown in this paper.

Let us look at the core of the problem. Being in a single collision domain, all stations in an *ad hoc* network contend for the same channel. In this case, basic access method based on CSMA/CA is proved to be an efficient channel access method. In an *infrastructure* network some stations appear hidden from each other, so contention for the channel is in a way blind. But all stations are in the transmission range of the AP and they are only allowed to exchange frames with the AP. When a station wants to transmit a data frame it transmits an RTS frame first. As every station hears CTS frames from the AP, collisions of data frames are completely avoided. In a "z" or "s" networks with multiple direct links, there is no guarantee that every station hears CTS frames from all recipients, so RTS/CTS exchange is not enough to protect direct transmissions.

As shown in many papers, e.g. [2]– [5], by means of simulation, some stations in such situations face starvation of channel access. Recently, authors have published the results of their analytical investigation of starvation problem arising in "z" or "s" networks [6]. We have explained in details why RTS/CTS exchange is inefficient when two direct links work in saturation.

While models based on ns2 or ns3 simulation tool are known to be rough for detailed study of such delicate issues as channel access (source code related to channel access does not follow the standard accurately), it is hardly possible to develop an analytical model to investigate the interaction of direct links in the case of normal load. So, to find out if the effect of starvation happens in a real network with normal load of various types of traffic, we deploy an outdoor testbed where some mesh stations are hidden from others.

In this paper, we develop an analytical model to investigate both basic access and RTS/CTS exchange (in)efficiency in protecting direct transmissions in saturation. Also, we report the results of our outdoor experiment, which show how big

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the starvation problem may be in a real network with normal load of real TCP and UDP traffic between mesh stations.

The rest of the paper is organized as follows. In the next section, we analyze the hardest case of direct link interference when one direct link “captures” almost all the channel capacity while the performance of another link suffers dramatically. In section III, the analysis is verified by the simulation results. In section IV, we describe a real deployment of a mesh network and show how dramatic the effect of starvation is even in the case of normal load. Conclusion summarizes the achieved results.

II. Analytical study

In our recent work [6] we studied several cases of stations disposition where the interference between two links leads to the performance degradation of one of them. In this paper for the reason of brevity, we describe only one case in which the throughput of two links differs dramatically and which is very common in mesh networks (see Figure 1). In [6] we assumed that RTS/CTS is used. In this work we extend our model for the basic access mechanism.

In Figure 1, STA1 – STA4 compose two active links: $1 \rightarrow 2$ and $3 \rightarrow 4$ working in saturation. The stations are located so that only the following pairs of stations are within the TX Range of each other: STA1 and STA2, STA2 and STA3, STA3 and STA4. Other pairs of stations do not interfere at all.

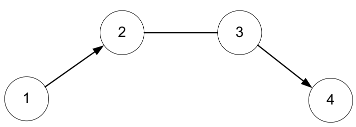

Fig. 1. Sample network

For both considered links we estimate such performance indices as:

- throughput S_m,
- probability $p_{rej}^{(m)}$ of packet rejection because of reaching a retry limit N_r, and
- average time $E_m[SendTime]$ of packet transmission,

where $m = 1$ or $m = 3$ correspond to the link sender's number. These performance indices are interconnected by the following equation:

$$S_m = \frac{L(1 - p_{rej}^{(m)})}{E_m[SendTime]}. \quad (1)$$

where L is the packet size (assumed to be constant).

As in [7], we refer to a time interval between two consecutive station's backoff decrements as the station's virtual slot. For a given station m counting its backoff, its virtual slot $t_{slot}^{(m)}$ can be empty (with length σ) or filled by other stations' transmissions (we denote its length as $l_a^{(m)}$). As STA1 and STA3 only transmit in our case, we obtain:

$$t_{slot}^{(m)} = (1 - \tau_n^{(m)})\sigma + \tau_n^{(m)} l_a^{(m)}, \quad (2)$$

where $\tau_n^{(m)}$ is the probability that STAn starts its transmission in the virtual slot of STAm, given STAm is aware of this transmission.

Let $p_c^{(m)}$ be the probability that a collision occurs when STAm transmits.

The average time of packet transmission is determined as follows:

$$E_m[SendTime] = a_0^{(m)} + \sum_{i=1}^{N_r-1} a_i^{(m)} (p_c^{(m)})^{(i-1)}, \quad (3)$$

where $a_i^{(m)}$ is the duration of the $(i+1)$th attempt, including the transmission time and the backoff time consisting of $\frac{W_i - 1}{2}$ slots on average, that is:

$$a_i^{(m)} = \frac{W_i - 1}{2} t_{slot}^{(m)} + (1 - p_c^{(m)}) l_s + p_c^{(m)} l_c^{(m)}, \quad (4)$$

where W_i is the contention window after i transmission attempts, l_s is the successful transmission duration, $l_c^{(m)}$ is the mean collision duration, and $t_{slot}^{(m)}$ is the mean virtual slot size.

For the RTS/CTS method, $l_s = l_s^R = RTS + CTS + DATA + ACK + DIFS + 3SIFS$. For the basic method, $l_s = l_s^B = DATA + ACK + DIFS + SIFS$.

Since we assume the absence of random noise, then for the considered case $p_{rej}^{(m)} = [p_c^{(m)}]^{N_r}$

To find the transmission probability $\tau_n^{(m)}$, we use the approach described in [8]. Considering a packet transmission process, we count the average number f_n of the packet transmission attempts and the average number w_n of virtual slots in which the station does not transmit during the process:

$$f_n = 1 + \sum_{i=1}^{N_r-1} (p_c^{(n)})^i,$$
$$w_n = \frac{W_0 - 1}{2} + \sum_{i=1}^{N_r-1} \frac{W_i - 1}{2} (p_c^{(n)})^i. \quad (5)$$

Then

$$\tau_n^{(m)} = \frac{f_n}{w_n + f_n} q_n^{(m)}, \quad (6)$$

where $q_n^{(m)}$ is the probability that a given STAn's transmission interrupts STAm's backoff.

Before proceeding with analysis, note that a transmission from STA3 to STA4 is always successful. Indeed, in case of simultaneous transmissions of STA1 and STA3 a collision occurs at STA2, but not at STA4, because it is hidden from STA1. So,

1) STA3 and STA4 always exchange their frames successfully, i.e. $p_c^{(3)} = 0$
2) STA1 can start its transmission at any time independently of STA3 and STA4, and
3) $q_3^{(1)} = 0$ and $q_1^{(3)} = 1 - p_c^{(1)}$ (see the explanation below).

A. Performance indices for the RTS/CTS method

Here, we describe an analytical model for the RTS/CTS method. First, to find the performance indices for link $3 \to 4$, we consider the cycle of STA3 operation which consists of STA3's transmission and backoff (see Figure 2).

It is reasonable to interpret $\tau_1^{(3)}$ as the probability that STA2 starts to reply to STA1 with a CTS frame during a backoff slot σ within the DIFS or backoff interval of STA3 (because in this case only STA1's transmission interrupts STA3's backoff).

The duration of STA3's virtual slot filled by STA1's successful transmission is $l_a^{(3)} = l_s^R - RTS - SIFS$, because STA3 does not hear the RTS sent by STA1.

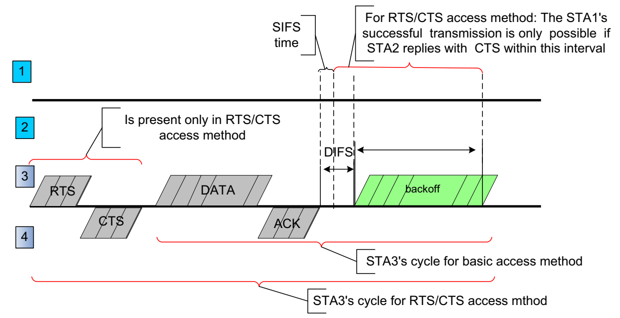

Fig. 2. Link $3 \to 4$ transmission cycle.

Interruption of STA3's DIFS count down is only possible after SIFS time after the beginning of DIFS. (Since STA2 uses virtual channel sensing mechanism, it does not react on the STA1's RTS arrived within the interval from the beginning of RTS from STA3 till the end of an ACK from STA4.) The length of the time interval within which STA2 replying to STA1 can interrupt STA3's DIFS is $d = \left[\hat{d} = \frac{DIFS - SIFS}{\sigma}\right]$ slots.

As mentioned before, STA3's transmission is always successful and its contention window is always minimal. So,

$$E_3[SendTime] = (l_s^R - DIFS + SIFS) + \\ + \left[d + \frac{W_0 - 1}{2}\right] t_{slot}^{(3)}. \qquad (7)$$

Now, consider link $1 \to 2$. STA1's transmission fails if it is started within interval $[t_{c_1}; t_{c_2}]$, where t_{c_1} corresponds to the $(RTS + SIFS)\mu s$ before STA3 starts RTS transmission, and t_{c_2} corresponds to the $(RTS + DIFS)\mu s$ before STA3 finishes to count its $DIFS$ (see Figure 2).

We can assume that STA1 may start transmitting its RTS with an equal probability at any instance within the STA3's cycle. The length of one cycle is $T_{cycle} \approx l_s^R + \frac{W_0 - 1}{2}\sigma$. Then, we find the probability of collision of STA1's RTS frame as the follows:

$$p_c^{(1)} = \frac{SIFS + l_s - DIFS}{T_{cycle}} \qquad (8)$$

and estimate performance indices of both links by (1)-(4), setting $l_a^{(1)} = \sigma$ and $l_c^{(1)} = \mathrm{RTS} + CTS_{timeout}$.

B. Performance indices for the basic access mechanism

Then, we find the performance indices for the basic access mechanism.

In this case, it is reasonable to interpret $\tau_1^{(3)}$ as the probability that STA2 starts to send ACK frame during a backoff slot σ within a backoff interval of STA3 in response to successful STA1's data frame (because only in this case STA1's transmission can interrupt STA3's backoff).

The duration of STA3's virtual slot filled by STA1's successful transmission is $l_a^{(3)} = ACK + DIFS$, because STA3 does not hear STA1's data transmission.

As STA3's transmission is always successful and its contention window is always minimal,

$$E_3[SendTime] = l_s^B + \frac{W_0 - 1}{2} t_{slot}^{(3)}. \qquad (9)$$

Now, consider link $1 \to 2$. STA1's transmission fails if it is started or ended during a STA3's data transmission.

For the basic method, a cycle of STA3 operation $T_{cycle} \approx l_s^B + \frac{W_0 - 1}{2}\sigma$.

Let us estimate STA1 collision probabilities. Let $t = 0$ correspond to the end of the last STA3's DATA frame transmission (see Figure 2). STA1's DATA transmission succeeds if it is started at $t_1 \in I(b) = [0, \Delta + b\sigma]$ and ended at $t_1^c \in I(b)$ (see Figure 2), where $\Delta = SIFS + ACK + DIFS$ and $b \in [0, W_0 - 1]$ is STA3's backoff time.

If STA1 starts its transmission at $t_1 \in I(b)$, it completes its data transmission by

$$t_1^c = t_1 + DATA, \qquad (10)$$

while STA3 completes counting its backoff by

$$t_3^c = \Delta + b\sigma. \qquad (11)$$

STA1's DATA frame transmission succeeds if $t_3^c \geq t_1^c$, i.e.,

$$b > b_0 = \lceil max\{0; (DATA - \Delta)/\sigma\} \rceil. \qquad (12)$$

So,

$$p_c^{(1)} = 1 - \frac{1}{T_{cycle}(W_0 - 1)} \times \\ \times \sum_{b=b_0}^{W_0 - 1} ((b - b_0)\sigma + max\{0; \Delta - DATA\}). \qquad (13)$$

Using (1)-(4) we find S_1 and S_3.

III. Numerical Results

In this section, we use our model to estimate performance indices of links $1 \to 2$ and $3 \to 4$ and compare the analytical results with those obtained by simulation in the General Purpose Simulation System (GPSS) environment [9]. Our simulation model follows all significant features of IEEE 802.11a protocol with rate 54 Mbps. The values of the protocol parameters used in our models are given in Table I.

TABLE I
VALUES OF PROTOCOL PARAMETERS.

Slot Time, σ	9 μs
CWmin	16
CWmax	1024
Payload, L	8196 bits
Retry threshold, N_r	7
ACK	24 μs
RTS, CTS	24 μs
DATA	180 μs
DIFS	34 μs
SIFS	16 μs

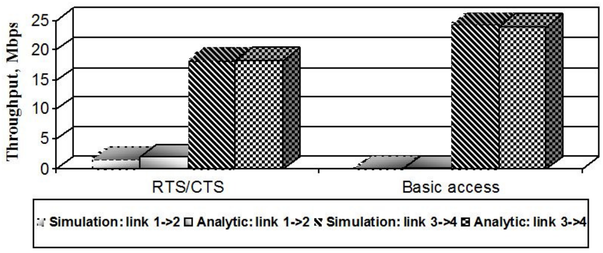

Fig. 3. Throughputs for the analytical and simulation models

In Figure 3, the throughputs obtained with analytical and simulation models are presented. Analytical and simulation results are almost coincide what proves that the analytical model is accurate enough.

Figure 3 shows that when STA1 is absolutely hidden from STA3 and STA4, throughputs for links $1 \rightarrow 2$ and $3 \rightarrow 4$ differ greatly.

These results can be explained as follows. When RTS/CTS method is used, with high probability, STA1 transmits its RTS during STA3-STA4 frame exchange and receives no answer from STA2. It makes STA1's contention window very long, and STA1 has small chances to access the channel, while the contention window of STA3 is minimal size, because STA3's data transmission is always successful. As a result, link $3 \rightarrow 4$ throughput is by order of magnitude greater than link $1 \rightarrow 2$ throughput.

For the basic access mechanism, the situation is even worse. As was shown in section II, when using basic access mechanism, collision probability of link $1 \rightarrow 2$ is highly dependent on packet size. Particulary, when a packet of 1KB is used (as in our models) a time share in which STA2 can successfully receive STA1's data frame is very small, while packets larger then 1.3 KB cannot be transmitted at all. This leads to unacceptably high collision probability and, hence, almost zero throughput. While the probability of packet rejection with the RTS/CTS method is 19%, with the basic method almost all packets are dropped.

IV. IMPLEMENTATION AND EXPERIMENTAL RESULTS

Models described above assume that all links work in saturation. To show that the described starvation effect emerges in the real life environment with real life traffic, we have deployed an outdoor test-bed. Our testbed consists of six

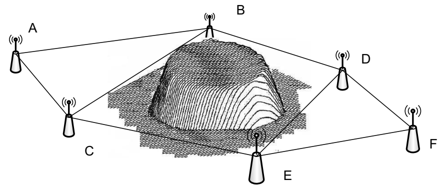

Fig. 4. Outdoor testbed

802.11a mesh stations connected with notebooks which are used to generate various kinds of traffic.

All mesh stations use the linux-based operating system, run a modified Atheros driver with rate adaptation functionality and use a reactive broadcast-based routing protocol called FLAME [10]. To find a route to a destination, a source node broadcasts its data frame. The first data frame reaching the destination determines the route.

To generate various kinds of traffic, we use IxChariot programming tool [11], which emulates traffic of real application and estimates the network performance.

The topology of a mesh network is shown in Figure 4 and characterized by SNR between each pair of nodes (see Tab. II).

Mesh stations are placed around a hill so that signals from nodes B and E (as well as from nodes C and D) do not interfere.

The distance between each pair of mesh stations is chosen so that mesh stations connected by a line in Figure 4 are within TX Range with each other, and mesh stations that are not connected by a line do not interfere at all.

Between each of the pairs – $A \rightarrow E$, $C \rightarrow D$, $B \rightarrow F$ – three concurrent traffic flows are launched:

- TCP flow with data rate of 512 Kbps and packet size of 1500 B (the "Best Effort" priority). This kind of flow corresponds to FTP transmission;
- UDP flow with data rate of 28 Kbps and packet size of 200 B (the video priority). This kind of flow corresponds to the transmission of streaming video with the lowest acceptable quality.
- UDP flow with data rate of 64 Kbps and packet size of 100 B (the voice priority).This kind of flow corresponds to the transmission of VoIP.

We measure the following performance indices for each connection:

- average, minimum and maximum throughputs;
- end-to-end delay and jitter;
- packet loss ratio.

The experiment results for all data flows are shown in Table III and IV.

The routes between each source and destination appear stable and consist of two hops. For B-F flow the route lies through node D; for C-D flow the route lies through node B and for A-E flow the route lies through node C.

TABLE IV
PERFORMANCE INDICES FOR FTP AND STREAMING VIDEO FLOWS

Flow direction	Average throughput, Kbps		Minimum throughput, Kbps		Maximum throughput, Kbps	
	FTP	Video	FTP	Video	FTP	Video
$A \rightarrow E$	57	27	9	22	523	28
$C \rightarrow D$	387	28	10	27	524	28
$B \rightarrow F$	467	28	25	28	523	28

TABLE II
SNR VALUES

Link	SNR, dB
A – B	9
A – C	9
B – C	19
B – D	22
C – E	9
D – E	10
D – F	9
F – E	12

TABLE III
PERFORMANCE INDICES FOR VOIP FLOWS

Flow direction	End-to-End Delay, ms	Jitter, ms	Packet Loss, %
$A \rightarrow E$	43	1,94	7,47
$C \rightarrow D$	45	1,89	1,89
$B \rightarrow F$	46	1,39	1,39

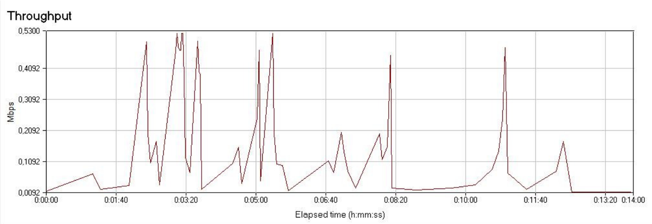

Fig. 5. The FTP flow throughput for A-E

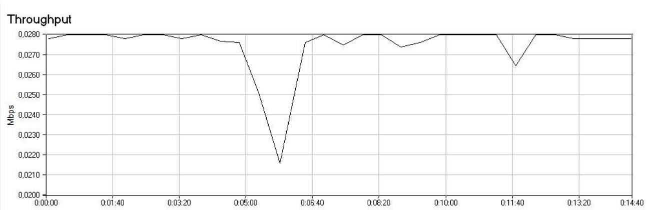

Fig. 6. The streaming video flow throughput for A-E

A. FTP traffic throughput

The comparison of plots for FTP traffic (see Figures 5, 8 and Table IV) shows that the throughput for C-D FTP flow and B-F FTP flow is much higher than for A-E FTP flow.

High throughput for B-F can be explained as follows: (1) node B does not have hidden terminals which are transmitting, hence the collision probability on B-D link is small and (2) no collision occurs on D-F link (node F successfully receives DATA frames even if nodes A, B or C are transmitting.

Dramatically low throughput for A-E FTP flow can be explained as follows. (1) Low SNR value of link C-E entails low transmission rate and high packet loss ratio. (2) The collision probability for link C-E is very high: during the transmission from D to F, node C senses the medium as idle and starts its transmission, which results in collision at node E with a frame from D. The second reason corresponds to stations disposition studied in section II. The unacceptably low value of the average throughput for A-E FTP flow proves that the starvation effect that was predicted by analytical and simulation models emerges in real environment.

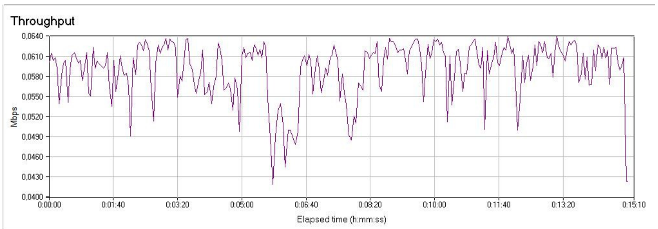

Fig. 7. The VoIP flow throughput for A-E

Throughput for C-D flow is much higher than for A-E flow due to high SNR values on C-B and B-D links. Also, stations C and B (which are both sources of the corresponding traffic) contend for the medium and have equal chances to win. Meanwhile C-D throughput is lower than for B-F flow because of high collision probability on C-B link (the reason of this is the same as for link C-E: during the transmission from D to F, node C senses the medium as idle and starts its transmission which results in collision at node B with a frame from node D.)

B. Video streaming and VoIP traffic throughput

For streaming video and VoIP traffic, the throughput is high enough for all pairs of sources and destinations (see Figures 6, 7, 9, 10 and Tables III and IV), and the packet loss rate and jitter remain acceptable.

It can be explained as follows. (1) Such types of traffic do not demand high link capacity and (2) such types of traffic have high priority, so, EDCA provides successful transmission of this traffic in spite of the presence of dense low priority traffic in the network.

However, bad quality of C-E link leads to increased jitter and packet loss ratio for A-E VoIP flow, comparing with B-F and C-D VoIP flows.

V. CONCLUSION

Driven by previous market success, IEEE 802.11 standard evolves by enabling new features and looking for new ap-

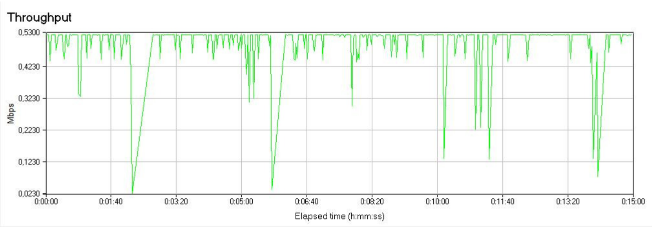

Fig. 8. The FTP flow throughput for B-F

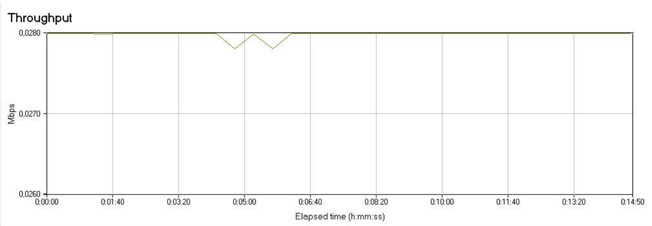

Fig. 9. The streaming video flow throughput for B-F

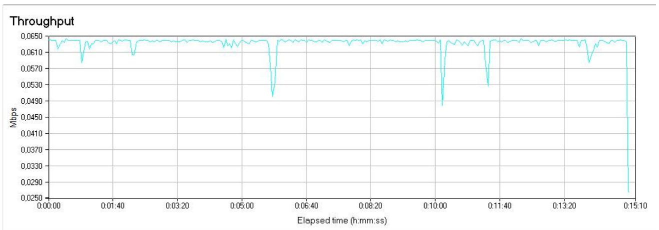

Fig. 10. The VoIP flow throughput for B-F

plication scenarios which will be able to drive its possible success in the market in future. Direct communication between stations in infrastructure networks allowed by Task Group "z" and mesh topology moved by Task Group "s" are the hottest topics for both academia and industry, which have potential to make the traditional network topologies fading away. However, the new topologies affect existing mechanisms in the network, and it is still to be fully understood how deep and fundamental the affect is.

In this paper, we investigate the effect of starvation in mesh networks where direct communication between stations affects such low-level functionality as the channel access method. Our analysis explains the roots of the phenomenon, and numerical results show that the problem is really hard: if links work in saturation some of them may be completely suppressed, meaning that the throughput of these links is close to zero.

To find out the scale of the problem in the case of normal load, but not in saturation, we deployed an outdoor testbed with real traffic such as Voice-over-IP, Video-over-IP and FTP. The results may be said satisfactory for low-rate VoIP traffic, but they are very depressing for FTP traffic of even 512kbps which is relatively low rate. It looks like direct link connectivity opens the Pandora box with hidden terminals, and standard RTS/CTS exchange fails to take them under control.

Fortunately, one may propose at least three methods to fight with interference caused by hidden terminals in mesh networks.

The first method is to use a routing protocol and a metric which would take into account hidden terminals and the direction of traffic flows in the network. Routes shall be chosen in a way to avoid the effect of starvation on some links.

The second method is the distributed reservation of the channel for the time of transmission. IEEE 802.11s draft [12] includes Mesh Coordinated Channel Access (MCCA) as an optional access method which allows mesh stations to access the wireless medium at selected times with lower contention than would otherwise be possible. Mesh stations advertise their channel reservations to two-hop neighborhood which reduces the probability of collision between hidden stations.

The third method consists in organizing of multi-channel network operation, when mesh stations use two or more PHY interfaces, each of them being tuned to a separate channel. By assigning channels to interfaces properly, it is possible to avoid the most severe case of links interference described in this paper.

Bad news is that none of these three methods is simple. Efficient methods for mesh network performance evaluation are needed to design, e.g., channel assignment algorithm. We hope that this paper will encourage future research to address this challenge.

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