

## CARRIER SENSE THRESHOLD/RANGE CONTROL

Compilation of MANET email messages

L. E. Miller, 5 January 2004

Subject: [manet] Carrier sense threshold/range control  
Date: Wed, 09 Jul 2003 12:08:35 -0400  
From: Ram Ramanathan <ramanath@bbn.com>

I am looking for pointers to research on the control of carrier sensing range in lieu of using RTS/CTS to address the hidden node problem?

To elaborate, the threshold for when carrier is declared to be "sensed" can be adjusted in many radios. Using this facility, one could possibly make the "carrier sense range" approximately twice the "communication range" (successful packet reception), and detect hidden nodes.

This is by no means a new idea, and I vaguely recall some mention of it on this list. Of course, there are a number of factors that make the problem far more complex than the simple statement above indicates, and it is not immediately clear whether it will be effective at all.

I am looking for papers, tech reports, or any publicly available material (non-proprietary) on this issue.

Many thanks in advance,

-Ram.

Subject: Re: [manet] Carrier sense threshold/range control  
Date: Wed, 09 Jul 2003 09:16:22 -0700  
From: Mineo Takai <mineo@cs.ucla.edu>

Hello Ram,

This issue was discussed in my part of a tutorial on "MAC protocols for MANET" (by Nitin Vaidya, Rajive Bagrodia and Mineo Takai) in MobiHoc 2001. Some of the slides seem to have corrupted, but you can take a look at Slides 31 through 34 of <http://www.scalable-networks.com/pdf/mobihocpreso.pdf>. I will try regenerating the slides and ask them to update.

Mineo

Subject: Re: [manet] Carrier sense threshold/range control  
Date: Wed, 09 Jul 2003 10:02:24 -0700  
From: Mineo Takai <mineo@cs.ucla.edu>

(I forgot to comment on this in my previous message other than giving a pointer..)

It is possible to avoid many hidden terminal cases by setting the sensing range more than twice the communication range, though there are some caveats. We can set/adjust the CS threshold, but not the pathloss that is to be determined by the environment. The CS range is a function of the CS threshold and pathloss (and TX power, antenna gains etc.), so the radio can hardly know what the resulting CS range is for a given CS threshold value. We can make each radio very sensitive by setting the CS threshold sufficiently low, but that would severely limit the network capacity as each radio becomes too conservative for signal transmission. Moreover, hidden terminal problems may show up regardless of the CS threshold due to irregular pathloss values. Imagine Nodes A, B and C are placed in an equal distance from each other (triangular topology), but Nodes B and C are obstructed by a wall that completely shuts down the communication link between them (pathloss equal to infinity). This clearly creates a hidden terminal problem at Node A regardless of the CS threshold. (RTS/CTS should still work in this situation.) Finally, other factors (fading, noise sources nearby, cumulative interference, interference/noise estimation errors etc.) make the CS mechanism less than perfect.

I'm not saying physical carrier sense is useless (In fact, I think it's very useful). Virtual carrier sense (RTS/CTS) is not a perfect solution either and comes with big overheads.

Mineo

Subject: RE: [manet] Carrier sense threshold/range control  
Date: Wed, 9 Jul 2003 10:37:34 -0700

From: "Yang, Lily L" <lily.l.yang@intel.com>

Is this threshold commonly adjustable in the driver for most 802.11 cards? I agree with Mineo that this threshold by itself may not be adequate for the hidden node problem. I would rather want to adjust the threshold to maximize the network capacity. As Mineo pointed out, when it is set too conservatively (which I think is the case), it causes the nodes to backoff unnecessarily and hence sacrifice spatial reuse potential and network capacity ultimately.

Subject: Re: [manet] Carrier sense threshold/range control

Date: Wed, 09 Jul 2003 15:37:06 -0400

From: Ram Ramanathan <ramanath@bbn.com>

> I'm not saying physical carrier sense is useless (In fact, I think it's very useful). Virtual carrier sense (RTS/CTS) is not a perfect solution either and > comes with big overheads.

>

> Mineo

Precisely. RTS/CTS also has the exposed terminal problem which is akin to being over-conservative on the sensing threshold (although not quite as bad). From your slides it seems like they are kind of competitive even if CS range is less than twice Comm range. So if I have two crummy mechanisms, why not choose the simpler one:)

I am not arguing a case here. Just wanted to know if someone has done a detailed comparison. Your tutorial comes closest, but is there a paper?

-Ram.

Subject: Re: [manet] Carrier sense threshold/range control

Date: Wed, 9 Jul 2003 15:51:43 -0400 (EDT)

From: "haas@ece.cornell.edu" <haas@ece.cornell.edu>

Hi Ram,

Actually, that's not entirely correct - the RTS/CTS dialogue will *in principle* solve both the hidden- and the exposed-terminal problems. The issue is that in practical situations it may fail, more specifically when some of the control messages (RTS or CTS) are lost due to transmission errors, mobility, etc.

There are a few papers relevant here. The first is the original MACA paper by Phil Karn that discusses the use of RTS/CTS instead of CS. The next is the MACAW paper that solves some residual problems for an indoor IR network (fairness, etc). Finally, there is our Dual Busy Tone Multiple Access (DBTMA) paper:

Zygmunt J. Haas and Jing Deng, "Dual Busy Tone Multiple Access (DBTMA)  
- A Multiple Access Control for Ad Hoc Networks," IEEE Transactions on  
Communications, vol. 50, no. 6, June 2002, pp. 975-985

which you can download from our web page at:

<http://wnl.ece.cornell.edu/wnlprojects.html>

and which contains the references to the MACA and the MACAW papers.

Best,

Zygmunt.

Subject: Re: [manet] Carrier sense threshold/range control

Date: Wed, 09 Jul 2003 13:34:24 -0700

From: ogier@erg.sri.com

Reply-To: ogier@erg.sri.com

> Actually, that's not entirely correct - the RTS/CTS dialogue will *in > principle* solve both the hidden- and the exposed-terminal problems. The issue is that in practical situations it may fail, more specifically when some of the control messages (RTS or CTS) are lost due to transmission errors, mobility, etc.

The problem with exposed terminals is that a node does not transmit even when it should (the opposite of the hidden terminal problem). RTS/CTS and CS both have the exposed terminal problem. Here is an illustration of the exposed terminal problem:  
<http://pcl.cs.ucla.edu/slides/workshop99/Ken-pw99/sld009.htm>

Richard

Subject: Re: [manet] Carrier sense threshold/range control  
Date: Wed, 9 Jul 2003 16:45:50 -0400 (EDT)  
From: "haas@ece.cornell.edu" <haas@ece.cornell.edu>

Hi Richard,

Yes, CS has the exposed terminal problem, but not RTS/CTS. In the slide that you have referenced, B transmits to A and C wants to transmit to D. When B send the RTS, it (temporarily) disables C from transmitting (for the duration of the RTS/CTS dialogue \*only\*). When A replies with CTS, this CTS is NOT heard by C (it is out of range), thus this CTS does not disable C from issuing RTS to D and (after this RTS/CTS dialogue concludes) transmit to D.

The bottom line, B can send to A while C sends to D; i.e., no exposed terminal exists here.

All this is in the original paper by Phil Karn on MACA.

However, RTS/CTS dialogue will fail to solve the hidden-terminal problem due to issues such as transmission errors, propagation delay, mobility, etc.

Zygmunt.

Subject: Re: [manet] Carrier sense threshold/range control  
Date: Wed, 9 Jul 2003 16:25:01 -0500 (CDT)  
From: "Dmitri D. Perkins" <perkins@cacs.louisiana.edu>

Dr. Haas,

Using the illustration referenced and assuming an RTS/CTS/DATA/ACK transmission scenario, the RTS must disable all nodes within range of B (since B must also receive an ACK from A). Using the same illustration, if C is allowed transmit to D while B is transmitting to A, how will B receive and ACK from A? It may now send C's transmission will like interfere.

Thus, the duration field of the RTS message must forced neighboring nodes to remain silent long enough for the sender (node B) to receive a CTS from node A + send a data frame to node A + recv an ACK from node A. The RTS duration field will also need to account for DIFS and SIFS (interframe spacing).

Now, if no ACK (an unreliable MAC) are used C should be allowed to transmit, but performance will suffer due to wireless channel effects.

Thanks,  
Dmitri Perkins

Subject: Re: [manet] Carrier sense threshold/range control  
Date: Wed, 09 Jul 2003 17:37:20 -0400  
From: John Stine <jstine@mitre.org>

>

> Yes, CS has the exposed terminal problem, but not RTS/CTS. In the slide that you have referenced, B transmits to A and C wants to transmit to D. When B send the RTS, it (temporarily) disables C from transmitting (for the duration of the RTS/CTS dialogue \*only\*). When A replies with CTS, this CTS is NOT heard by C (it is out of range), thus this CTS does not disable C from issuing RTS to D and (after this RTS/CTS dialogue concludes) transmit to D.

But won't C have to wait for a DIFS after the RTS/CTS NAV resulting in enough time for B to start sending its packet prior to C sending an RTS. C will have to defer again.

The classic example of an exposed node is the node on a mountain that can hear two disjoint sections of a network on either side of the mountain. Call the set of nodes on one side of the mountain Network A and the nodes on the opposite side Network B. Nodes in Network A cannot hear Network B and vice versa. The exposed node hears both. The exposed node is at a disadvantage in gaining access and in receiving packets. In order for this node to transmit or receive both sides must be

silent. The latter is not as obvious. If a node in network A sends an RTS to the exposed node and a transmission is already occurring in Network B, the exposed node cannot respond with a CTS since this may interfere with the reception in Network B. Thus the exposed node defers from responding. The node that sent the RTS to the exposed node chalks it up as a failure and retries. It will be pure chance that the node in network A will initiate a transmission to the exposed node during a period when Network B is silent. Certainly if Network B is silent and the exposed node receives the RTS from a node in Network A then the exposed node's CTS will silence Network B. Geography is not the only thing that can expose a node. Disjoint packet flows in an ad hoc network may also cause a node that hears both to be effectively exposed. The RTS/CTS handshake does nothing to prevent this exposure and exacerbates the problem because of the virtual sensing requirement.

Subject: Re: [manet] Carrier sense threshold/range control  
Date: Wed, 9 Jul 2003 17:39:34 -0400 (EDT)  
From: "haas@ece.cornell.edu" <haas@ece.cornell.edu>

Hi Dmitri,

On Wed, 9 Jul 2003, Dmitri D. Perkins wrote:

> Using the illustration referenced and assuming an RTS/CTS/DATA/ACK transmission scenario, the RTS must disable all nodes within range of B (since B must also receive an ACK from A). Using the same illustration, if C is allowed transmit to D while B is transmitting to A, how will B receive and ACK from A? It may now send C's transmission will like interfere.

Please note that I referred to the RTS/CTS dialogue only, and not to the RTS/CTS/DATA/ACK exchange. In the former, there is no need for RTS to disable the nodes around the transmitter for more than the duration of the RTS/CTS exchange only. Thus, while B transmits DATA to A, C is not disabled and can transmit to A.

You are correct in saying that RTS/CTS/DATA/ACK dialogue requires to disable nodes around both, the transmitter and the receiver, just to cover the ACK going back to the transmitter. But this is not the case in "pure" RTS/CTS dialogue, where the ACK can be sent on higher layer than the MAC.

Hopes this clarifies the issue.

Zygmunt.

Subject: [manet] Re: Carrier sense threshold/range control  
Date: Wed, 9 Jul 2003 17:03:50 -0500 (CDT)  
From: "Nitin H. Vaidya" <n hv@crhc.uiuc.edu>

Reading manet mails in digest mode .... so comments on several messages lumped together.

. >>From: Ram Ramanathan <ramanath@bbn.com>

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. >>To elaborate, the threshold for when carrier is declared to be "sensed" can be adjusted in many radios. Using this facility, one could possibly make the "carrier sense range" approximately twice the "communication range" (successful packet reception), and detect hidden nodes.

If I recall correctly, the paper on Wavelan (the first Wavelan) that appeared in Bell Labs journal (AT&T journal, or whatever it was called at the time), shows a picture that matches with your discussion above. I think they chose a carrier sense range twice that of the transmission range -- it seems that the Bell Labs Technical Journal has disappeared from the web, so I cannot find the paper (which was written by Bruce Tuch).

. >>From: "haas@ece.cornell.edu" <haas@ece.cornell.edu>

. >>

. >>Actually, that's not entirely correct - the RTS/CTS dialogue will \*in principle\* solve both the hidden- and the exposed-terminal problems.

It will solve the hidden terminal problem if the nodes that interfere with the reception at a host R are also the nodes that reliably receive the transmission of CTS from host R -- this may not be the case.

. >>From: "Dmitri D. Perkins" <perkins@cacs.louisiana.edu>

. >>

>>Using the illustration referenced and assuming an RTS/CTS/DATA/ACK ransmission scenario, the RTS must disable all nodes within range of B (since B must also recieve an ACK from A). Using the same illustration, if C is allowed transmit to D while B is transmitting to A, how will be B receive and ACK from A? It may now send C's transmission will like interfere.

. >>

. >>Thus, the duration field of the RTS message must forced neigboring nodes to remain silent long enough for the sender (node B) to receive a CTS from node A + send a data frame to node A + rcv an ACK from node A. The RTS duration field will also need to account for DIFS and SIFS (interframe spacing).

. >>

. >>Now, if no ACK (an unreliable MAC) are used C should be allowed to transmit, but performance will suffer due to wireless channel effects.

Zygmunt is refering to MACA I think, whereas you might be referring to 802.11. Both are right, of course, Incidentally, 802.11 is conservative in the manner in which collisions with ACKs are prevented (neighbors of the senders only need disable transmissions during the ACK reception at the sender, but 802.11 disables them for the entire transaction -- that simplifies NAV maintenance).

nitin

Subject: Re: [manet] Carrier sense threshold/range control  
Date: Wed, 9 Jul 2003 15:09:49 -0700  
From: "Alaa Muqattash" <alaa@ece.arizona.edu>

Prof Haas,

So the "pure" RTS/CTS dialogue, where the ACK can be sent on higher layer than the MAC is \*end-to-end\* reliability mechanism. A more efficient method is to use ACK in \*each hop\* transmission. This would require the MAC layer to send back the ACK (and not any upper layer), thus, the RTS must silence nodes in the vicinity of the transmitter. The question is: Would the advantage MAC reliability (each hop ACK)offset the disadvantage of reserving the floor around the transmitter?

Best regards,  
Alaa Muqattash

Subject: Re: [manet] Carrier sense threshold/range control  
Date: Wed, 9 Jul 2003 18:16:39 -0400 (EDT)  
From: "haas@ece.cornell.edu" <haas@ece.cornell.edu>

Hi Alaa,

There is no simple answer to your question - it depends on the various parameters of the system, such as the success prob of a single hop, the (end-to-end) path length, etc.

Zygmunt.

Subject: RE: [manet] Carrier sense threshold/range control  
Date: Wed, 9 Jul 2003 16:42:45 -0600  
From: "John Mullen" <jomullen@nmsu.edu>

Hi Alaa,

The advantage of the link-by-link ACK is primarily that intermediate nodes can flush the packet from their buffers as soon as they know it has been sent on. Without it, a lot of buffer space can be needlessly tied up.

In many cases, and explicit ACK is not needed. Say we have A-B-C and A sends a packet to B intended for C. If B receives the packet and sends it to C, in most cases, A will be able to overhear B's transmission and be able to deduce that B has received the packet. An explicit ACK would be needed for the B-C link because C would not retransmit, so B will set the ACK flag in its transmission. On the other hand, if C would send an end-to-end ACK back to A anyways, B would not need to set the flag. An ACK would also be needed if A did not hear enough of the retransmitted packet to know it is B's relay.

Usually, A waits for a timeout and either resends with a request for an explicit ACK. In most cases, however, this is unnecessary, saving the need to ACK.

John Mullen

Subject: RE: [manet] Carrier sense threshold/range control  
Date: Wed, 9 Jul 2003 16:43:42 -0600  
From: "John Mullen" <jomullen@nmsu.edu>

Hi Zygmunt,

Well, there is still a problem or two with RTS/CTS alone.

Say, as in the illustration, B wishes to send to A. Terminal B sends a RTS, which C hears. However, C never hears the CTS from A because A is too far away. What are C's choices if it wishes to send to D? One is to hold off for a random period of time, just in case A intends to send a CTS. If A doesn't send a CTS, then C has missed an opportunity to send. On the other hand, if C sends its RTS, it may cause a data collision at B. Assuming C cannot hear A, it is not possible for C to know.

Of course, once B starts to transmit, the risk of a collision at B is not a problem, but now C would not be able to hear a CTS from D due to interference from B. In theory, C can send to D without causing a problem, but in practice, unless the timing is just right, C will not know that.

Unless terminals have perfect knowledge of the local topology and exactly what each of their neighbors are doing, it will not be possible to eliminate both the hidden and exposed terminal problems entirely. It should also be borne in mind that one can include in RTS and CTS an estimate of the duration of the channel's use so terminals that can hear will know how long to wait before trying to seize the channel. Carrier sensing, while useful, does not have this capability.

An interesting approach is in the paper "Floor Acquisition Multiple Access (FAMA) for Packet-Radio Networks," available at <http://citeseer.nj.nec.com/fullmer95floor.html>

In FAMA, time slots are reserved for RTS and CTS so data and control packets do not collide. Furthermore, the authors contend that data packets will never collide. The trade-off, of course, is the number of time slots to reserve for signaling. I'm not that current on MAC protocols and there may be more recent papers.

John Mullen

Subject: RE: [manet] Carrier sense threshold/range control  
Date: Wed, 9 Jul 2003 18:44:53 -0400 (EDT)  
From: "haas@ece.cornell.edu" <haas@ece.cornell.edu>

Hi John,

> Say, as in the illustration, B wishes to send to A. Terminal B sends a RTS, which C hears. However, C never hears the CTS from A because A is too far away. What are C's choices if it wishes to send to D? One is to hold off for a random period of time, just in case A intends to send a CTS. If A doesn't send a CTS, then C has missed an opportunity to send. On the other hand, if C sends its RTS, it may cause a data collision at B. Assuming C cannot hear A, it is not possible for C to know.

The MACA algorithm that I was referring to allows RTS to "reserve" the channel for the duration of the RTS/CTS exchange only. Thus C will be disabled for the duration of that time only. There is no need for C to guess - if it did not hear CTS by the end of this period, it is free to access the channel.

Again, the correctness of the MACA protocol depends on its theoretical assumptions that there are no transmission errors, etc ... i.e., if a RTS or CTS packet is sent, it is reliably received by all the nodes in the vicinity of the respective transmitter.

> Of course, once B starts to transmit, the risk of a collision at B is not a problem, but now C would not be able to hear a CTS from D due to interference from B. In theory, C can send to D without causing a problem, but in practice, unless the timing is just right, C will not know that.

Correct. This issue (and few others) were addressed in the MACAW paper.

My statement was that under some theoretical assumptions, MACA provides for both hidden- and exposed-terminal problems. In practice, as I have stated, this is incorrect. This is why other schemes came in to fill in the gap, the FAMA, as you have mentioned, and the DBTMA, as I have.

Cheers ... (I am off the line - have to do some work today ...(-;-)).

Zygmunt.

Subject: Re: [manet] Re: Carrier sense threshold/range control  
Date: Wed, 9 Jul 2003 17:53:22 -0500 (CDT)  
From: "Dmitri D. Perkins" <perkins@cacs.louisiana.edu>

Question...Referencing the previous illustration (A<-----B C----->D), is there any work showing the benefit versus overhead or complexity for the following scenario:

1. allow node C to transmit to D while B is transmitting a data frame to A
2. force C to keep silent just in time for B to receive the ACK from A.

This MAY result in better channel utilization but SHOULD require a more complex access/NAV scheme. Any thoughts...

BTW...

Regarding the use of end-to-end ACKs versus MAC-layer ACKs, if we compare the performance of TCP over CS/RTS/CTS/DATA/ACK versus CS/RTS/CTS/DATA versus CS/DATA, TCP over CS/RTS/CTS/DATA/ACK will typically perform better. I believe Gerla's group at UCLA has published some work on this issue. Of course, one cause of the decreased throughput when using TCP is the use of slow-start when a packet loss occurs. Any thoughts...

Thanks,  
Dmitri

Subject: RE: [manet] Carrier sense threshold/range control  
Date: Wed, 9 Jul 2003 17:00:44 -0600  
From: "John Mullen" <jomullen@nmsu.edu>

Hi Zygmunt,

(For when you get back :-)

In my little example, I was referring to protocol design choices. The protocol would, of course, remove any ambiguity from C's little mind. My point was that if you use a hold-off, as in MACA, you have the exposed terminal problem and if you do not, you now have a hidden terminal problem, of sorts. (C may know B is there, but doesn't know that A is sending). Since you must do one or the other, you cannot eliminate both problems entirely.

As for the realities of noise and random fluctuations. Well, that is what makes this whole thing interesting. A couple of years ago, I was on the committee of a Ph.D. student studying protocols for outer space transmission. He worked quite a while in an error free environment. I and other members of the committee urged him to include the noise before drawing too many conclusions, but he was a depth-first-search kind of guy. Finally, he put in the noise. I remember him showing me the effect. It was quite remarkable, as I expected. His carefully analyzed order of performance among the protocols was completely trashed by the effects of noise.

:-)

John Mullen  
p.s. thanks for the link.  
(Is this an ACK?)

Subject: [manet] Re: Carrier sense threshold/range control  
Date: Wed, 9 Jul 2003 18:09:04 -0500 (CDT)  
From: "Nitin H. Vaidya" <nvh@crhc.uiuc.edu>

On Wed, 9 Jul 2003, Dmitri D. Perkins wrote:

. >>Question...Referencing the previous illustration (A<-----B C----->D),

. >>is there any work showing the benefit versus overhead or complexity for  
. >>the following scenario:  
. >>  
. >>1. allow node C to transmit to D while B is transmitting a data frame to A  
. >>2. force C to keep silent just in time for B to receive the ACK from A.  
. >>  
. >>This MAY result in better channel utilization but SHOULD require a more  
. >>complex access/NAV scheme. Any thoughts...

In the above scenario, C needs to sneak in its DATA (and perhaps RTS) packet between the reception of CTS and ACK node B. This may not be feasible (depends on packet sizes).

The gains could be much more interesting in the scenario below, which simply reverses directions of the data transmissions (provided that A does not pose too much interference at C, and D at B).

A -----> B      C <----- D

nitin

Subject: Re: [manet] Re: Carrier sense threshold/range control  
Date: Wed, 9 Jul 2003 16:29:54 -0700  
From: "Alaa Muqattash" <alaa@ece.arizona.edu>

> The gains could be much more interesting in the scenario below, which simply reverses directions of the data transmissions (provided that A does not pose too much interference at C, and D at B).

>  
> A -----> B      C <----- D  
>

This is exactly what PCMA and PCDC do (see reference below); they allow nodes to access the channel simultaneously only if the interference is \*not high enough\* to cause collisions at the receivers. However, note that they use two channels and are not compatible with the 802.11 approach.

Jeffrey P. Monks, Vaduvur Bharghavan, and Wen-mei Hwu, "A Power Controlled Multiple Access (PCMA) Protocol for Wireless Packet Networks," IEEE INFOCOM 2001, Anchorage, Alaska, April, 2001

Alaa Muqattash and Marwan Krunz "Power Controlled Dual Channel (PCDC) Medium Access Protocol for Wireless Ad Hoc Networks," in the Proceedings of the IEEE INFOCOM'03 Conference, San Francisco, April 2003.

Subject: Re: [manet] Re: Carrier sense threshold/range control  
Date: Wed, 9 Jul 2003 18:39:53 -0500 (CDT)  
From: "Nitin H. Vaidya" <n hv@crhc.uiuc.edu>

. >>This is exactly what PCMA and PCDC do (see reference below); they allow

Not quite the same as PCMA ... since the basic RTS/CTS mechanisms do not explicitly look at SNR, unlike PCMA.

In any case, I think I got the example wrong in that it may not be any more interesting than the example with the flows in opposite directions. If B and C above were closer though, one could conceive a bit smarter MAC -- for instance, if C hears the RTS received by B from A, then C can overlap its RTS with the CTS it expects B to send to A. Too complex for this time of the day ...

nitin

Subject: Re: [manet] Carrier sense threshold/range control  
Date: Wed, 09 Jul 2003 22:49:23 -0700  
From: ogier@erg.sri.com

John and Zygmunt,

> In my little example, I was referring to protocol design choices. The protocol would, of course, remove any ambiguity from C's little mind. My point was that if you use a hold-off, as in MACA, you have the exposed terminal problem and if you do not, you now have a hidden terminal problem, of sorts. (C may know B is there, but doesn't know that A is sending). Since you must do one or the other, you cannot eliminate both problems entirely.

In fact, you cannot eliminate the exposed terminal problem completely, since (as you pointed out), if C sends an RTS to D while B is sending data to A, then C will not hear the resulting CTS from D. Therefore, it seems to me that even "pure" RTS/CTS does not solve the exposed terminal problem even in ideal conditions. I looked at the MACAW paper (Bhargavan et al.) today to see if it solves the exposed terminal problem, and it actually has a mechanism (Data-Sending packet) that \*prevents\* C from sending anything while B is sending data to A.

Richard

Subject: RE: [manet] Carrier sense threshold/range control  
Date: Thu, 10 Jul 2003 14:29:12 +0800  
From: "#LI ZHIFEI#" <zhifeili@pmail.ntu.edu.sg>

It seems that the RTS/CTS handshake in single channel cannot eliminate the hidden-terminal and exposed-terminal problem. But the DBTMAC seems to solve these two problems completely with two additional busy tone channel (rather than send the control frames in the same data channel).

Subject: RE: [manet] Carrier sense threshold/range control  
Date: Thu, 10 Jul 2003 07:50:36 -0600  
From: "John Mullen" <jomullen@nmsu.edu>  
To: <manet@ietf.org>

Hi Li,

What you say is correct, but only to a point and with a reservation. First of all, although you can avoid collisions on the data channel, I don't think you can avoid them completely on the busy tone channels. The more significant problem is that you are reserving part of your available spectrum for signaling. Whether this is done with a separate radio channel or with time division on a single channel, you are allowing only a fraction of the allotted band for data. Thus, you need to determine how much of the channel(s) need to be reserved for signaling. This would be a design matter and probably a tuning parameter, since the distribution of message lengths would determine the optimal signaling/data ratio.

This is not to say that such a thing is a bad idea, just that if not done properly, it could be an inefficient use of the available spectrum.

John Mullen

Subject: RE: [manet] Carrier sense threshold/range control  
Date: Thu, 10 Jul 2003 10:03:38 -0400 (EDT)  
From: Chien-Chung Shen <cshen@mail.eecis.udel.edu>

Greetings,

We have paper that compared (omnidirectional) 802.11, MACA, and DBTMA, and their directional versions (with directional antenna) published in IEEE Globecom, 2002.

Zhuochuan Huang and Chien-Chung Shen A Comparison Study of Omnidirectional and Directional MAC Protocols for Ad hoc Networks

Thanks.  
Chien-Chung

Subject: RE: [manet] Carrier sense threshold/range control  
Date: Thu, 10 Jul 2003 22:06:21 +0800  
From: "#LI ZHIFEI#" <zhifeili@pmail.ntu.edu.sg>

>What you say is correct, but only to a point and with a reservation. First of all, although you can avoid collisions on the data channel, I don't think you can avoid them completely on the busy tone channels.

As for my understanding, in the busy channels, other potentially interfering nodes need not interpret the content but just sensing the existence of busy carrier. So what do you mean for the collisions on the busy channel?

>The more significant problem is that you are reserving part of your available spectrum for signaling. Whether this is done with a separate radio channel or with time division on a single channel, you are allowing only a fraction of the allotted band for data. Thus, you need to determine how much of the channel(s) need to be reserved for signaling. This would be a design matter and probably a tuning parameter, since the distribution of message lengths would determine the optimal signaling/data ratio.

>This is not to say that such a thing is a bad idea, just that if not done properly, it could be an inefficient use of the available spectrum.

I accept your viewpoint without any doubt. In addition to the issue about the spectrum efficiency, complexity may be another issue by introducing multiple channels.

Best regards  
Li zhifei

Subject: RE: [manet] Carrier sense threshold/range control  
Date: Thu, 10 Jul 2003 22:08:29 +0800  
From: "#LI ZHIFEI#" <zhifeili@pmail.ntu.edu.sg>

Hi, Ram

In my view, even the Carrier Sensing Range (SR) is two times of the Transmission Range (TR), the hidden-terminal problem is still there. This can be illustrated as the following two topologies:

Topology 1:

A -> B <- C

Topology 2:

A -> B C <- D

(note that the distance between two neighboring nodes are equal to the transmission range, i.e., one hop)

The first topology is typically used to illustrate the well-known hidden-terminal problem, but with an implicit assumption, i.e.,  $SR=TR$ . If  $SR=2*TR$ , the hidden-terminal problem seems not exist any more in this topology as the nodes A and C can sense the transmission of each other.

However, even  $SR=2*TR$ , the problem will arise in the second topology. Specically, when node A starts to transmit to node B, since node D is out of the SR of node A, it cannot detect the transmission. Therefore, node D may also start to transmit to node C, resulting in collision (or capture). In such case, we can say that nodes A and D are hidden terminal of each other. We do find the similarities of the performance between the two cases: topology 1 when  $SR=TR$ ; and topology 2 when  $SR=2*TR$

When  $SR>TR$ , another problem is that how a node should defer its transmission when it detects a SR frame. This is not an easy job since the node cannot interpret the content of the SR frame. In the IEEE 802.11, whenever a node detects a SR frame, it will defer by a fixed EFIS value. However, our results show this fixed value will cause many problems, e.g., unfairness. Moreover, the capture ability will also greatly affect the performance when  $SR>TR$ . For a detailed description of these issues, please refer to the attached references:

Zhifei Li, Sukumar Nandi, Anil K. Gupta, "Improving Fairness in IEEE 802.11 based MANETs using Enhanced Carrier Sensing", submitted to conference, April 2003  
<http://www.ntu.edu.sg/home5/pg03802331/papers/ecs.pdf>

Zhifei Li, Sukumar Nandi, Anil K. Gupta, "Study of IEEE 802.11 Fairness and its Interaction with Routing Mechanism", accepted by IEEE MWCN 2003 Singapore, May 2003  
<http://www.ntu.edu.sg/home5/pg03802331/papers/mwcn03.pdf>

Though the above papers mainly focus on the fairness issue when  $SR > TR$ , the description should also apply to the analysis of the channel utilization. I hope that they will relate to your work and help you.

Best regards  
Li ZhiFei

Subject: RE: [manet] Carrier sense threshold/range control  
Date: Thu, 10 Jul 2003 11:02:00 -0400  
From: Vikram Dham <vdham@vt.edu>

Hello Zhifei Li,

Though topology 2 also may have scenarios with hidden terminal, but in a wireless network, probability (distance between nodes  $> 2SR$ )  $\Rightarrow$  probability (distance between nodes  $> SR$ ).

Though we may not be eliminating all the hidden terminals but we may decrease the probability of occurrence of hidden terminals by extending sensing range to  $2SR$ .

Regards  
Vikram Dham

Subject: RE: [manet] Carrier sense threshold/range control  
Date: Thu, 10 Jul 2003 12:05:00 -0600  
From: "John Mullen" <jomullen@nmsu.edu>

Hi Li,

I'm not entirely sure how you use the busy tone channels, so my statement may not be correct. However, a fundamental problem is in how a terminal gets the right to use a channel. If terminals transmit RTSs as the need arises, there is always a chance that those of different terminals will collide with each other. This contention will have to occur somewhere, whether on the signaling channel or the data channel. So, wherever this signaling occurs is where the problem will be.

Another problem is the short, but significant, transmission delay. A terminal may sense that the busy channel is idle and begin to transmit, unaware that another terminal has made the same decision. Because the carrier takes a finite, though brief, time to reach the other terminal and there is inherent delay in the sensing and control processes, by the time the carrier could be sensed, the terminal will already be sending.

Later,  
John Mullen

Subject: Re: [manet] Re: Carrier sense threshold/range control  
Date: Thu, 10 Jul 2003 15:44:31 -0400 (EDT)  
From: Jing Deng <jdeng01@ecs.syr.edu>

Prof. Vaidya,

In the first scenario, node C may not be able to sneak in its RTS and DATA packet transmissions even if their lengths are short enough. The problem is that it won't be able to receive node D's CTS reply correctly. Thus, if the RTS/CTS/DATA handshakes are implemented on a single channel (and assuming the same transmission ranges), the exposed terminals should never try to send their RTS requests.

So node C may have only one choice: keep silent while node B is sending. If an ACK packet is to be transmitted back to node B (the DATA packet sender), node C may want to be quiet for a little bit longer.

It will be another story if out-of-band signaling or multiple channels are in use.

Jing

Subject: RE: [manet] Carrier sense threshold/range control  
Date: Thu, 10 Jul 2003 16:37:55 -0400  
From: "Chi-Hsiang Yeh" <chi-hsiang.yeh@ece.queensu.ca>

Hi, John,

> I'm not entirely sure how you use the busy tone channels, so my statement may not be correct. However, a fundamental problem is in how a terminal gets the right to use a channel. If terminals transmit RTSs as the need arises, there is always a chance that those of different terminals will collide with each other. This contention will have to occur somewhere, whether on the signaling channel or the data channel. So, wherever this signaling occurs is where the problem will be.

What you said is correct in that contention will occur somewhere. But DBTMA uses busy tone and such busy tone does not have the collision problem (as Zhifei pointed out). Using this and other properties, data packet transmissions are collision-free in DBTMA even when some RTS/CTS messages are collided, "under certain assumptions" (e.g., when the following Problems (1-3) do not exist). We have another protocol (that does not require busy tone) where data packets and RTS/CTS control messages are both collision-free, under certain assumptions. See

You, T., C.-H. Yeh, and H. Hassanein, "A new class of collision-prevention MAC protocols for ad hoc wireless networks," ICC, May 2003.

When there are two separate channels for data packets and control messages, the hidden terminal problem and the exposed terminal problem can both be solved easily and simultaneously, but only theoretically. In practice, due to the following problems DBTMA and our protocol are not really collision-free, and most previous MAC protocols (including DBTMA and our ICC'03 protocol) still suffer from some forms of hidden/exposed terminal problems:

(1) The propagation properties of the control channel and data channel may be different. As a result, a node that receives a CTS message actually may not collide the associated reception (and thus a form of the exposed terminal problem exists). Moreover, a node that did not receive a CTS message may actually collide the associated reception (and thus a form of the hidden terminal problem exists). No matter how you adjust the power levels of the control channel and busy tone, one or both of the problems exist.

(2) In most papers it is assumed that transmission radius (TR) = interference radius (IR). When  $IR > TR$ , then a node with distance between TR and IR will collide a reception. This problem might be fixed when you have separate channels -- by sending RTS/CTS messages with a radius at least IR or at an appropriate power level.

(3) Assume that (1) and (2) are not problems. Then two or more nodes that did not receive a CTS message may still collide the associated reception due to their "additive interference" (and thus a form of the hidden terminal problem exists). This problem is more difficult to solve than Problem (2). PCMA might "solve" this problem, but it suffers from Problem (1) and overhead/complexity/hardware cost.

(4) When two or more nearby nodes transmit busy tone simultaneously, the strength received at a node is increased. So a node that should not have received any busy tone may actually detect such "additive busy tone" and defer its transmissions (and thus a form of the exposed terminal problem exists).

Note that the above problems are not the hidden terminal problem and the exposed terminal problem identified in the Tobagi and Kleinrock paper (in IEEE Trans. Communications, 1975). They have some similarity in principle, but are not exactly the same problems.

It's not impossible to solve all these problems, but the resultant protocol will not necessarily outperform existing protocols due to its overhead, and the resultant hardware may be more expensive.

Chihsiang

Subject: RE: [manet] Carrier sense threshold/range control  
Date: Thu, 10 Jul 2003 16:58:02 -0400 (EDT)  
From: Jing Deng <jdeng01@ecs.syr.edu>

Dr. Mullen,

I agree with you. It will be very difficult to eliminate collisions when distributed nodes (such as those in MANETs) are competing for a single shared channel. Due to signal propagation delays, carrier sensing delays, and processing delays, collisions will still exist even if carrier sensing technique is used (as you have assumed).

However, if we use the busy tone or signaling channels properly, data packet collisions can be avoided. Only channel requests (RTS packets) are subject to possible collisions. Since the RTS packets are of much shorter length, performance gain of throughput can still be achieved.

In what ratio the single channel is split affects the performance of the MAC scheme significantly (as you pointed out in your earlier post), especially when the RTS/CTS dialogues are to be transmitted on the control channel. We have found some interesting results and shown them in the following paper:

J. Deng, Y. S. Han, and Z. J. Haas, "Analyzing Split Channel Medium Access Control Schemes with ALOHA Reservation," ADHOC-NOW '03, Montreal, Canada, October 8-10, 2003. (to appear)

I will be happy to share it with anyone who is interested.

Cheers,  
Jing

Subject: RE: [manet] Re: Carrier sense threshold/range control  
Date: Thu, 10 Jul 2003 17:25:08 -0400  
From: "Chi-Hsiang Yeh" <chi-hsiang.yeh@ece.queensu.ca>

Hi, Nitin,

> . >>> The gains could be much more interesting in the  
> scenario below, which . >>> simply reverses directions of  
> the data transmissions (provided that . >>> A does not pose  
> too much interference at C, and D at B). . >>>  
> . >>> A -----> B      C <----- D  
> . >>>  
> . >>> - nitin  
> . >>  
> . >>>This is exactly what PCMA and PCDC do (see reference  
> below); they allow  
>  
> Not quite the same as PCMA ... since the basic RTS/CTS  
> mechanisms do not explicitly look at SNR, unlike PCMA.  
>  
> In any case, I think I got the example wrong in that it may not be any more interesting than the example with the flows in  
opposite directions. If B and C above were closer though, one could conceive a bit smarter MAC -- for instance, if C hears the  
RTS received by B from A, then C can overlap its RTS with the CTS it expects B to send to A. Too complex for this time of  
the day ...

Could you explain your strategy (and the assumed scenario) more clearly? If C sends RTS then C is a transmitter and what you  
said is neither the above "A->B C<-D" scenario nor the "A<-B C->D" scenario (in Dmitri's mail). If C sends CTS and uses  
MACA/BI-type of mechanisms, the resultant strategy still has fundamental problems besides its complexity...

Chihsiang

Subject: RE: [manet] Re: Carrier sense threshold/range control  
Date: Fri, 11 Jul 2003 10:12:24 +0800  
From: "#LI ZHIFEI#" <zhifeili@pmail.ntu.edu.sg>

hi, prof. Nitin

> If B and C above were closer though, one could conceive a bit smarter MAC -- for instance, if C hears the RTS received by B  
from A, then C can overlap its RTS with the CTS it expects B to send to A. Too complex for this time of the day ...

The problem for me is as follows:

If node C can overhear the transmission of the RTS from node A to node B, then, any transmission from node C will  
interfere the frame reception at node A. Of course, we hold the symmetry assumption.

So how could the transmission of RTS (from C) and the transmission of CTS (from B ) can overlap?

li zhifei

Subject: RE: [manet] Carrier sense threshold/range control  
Date: Fri, 11 Jul 2003 10:32:17 +0800  
From: "#LI ZHIFEI#" <zhifeili@pmail.ntu.edu.sg>

Yes, the objective of the handshaking (RTS/CTS/Data/ACK) is mainly to protect the Data frame, which is normally long. Therefore, the collision of short RTSs will not affect the channel utilization too much. However, it will result in major problems if we consider fairness. As for the CTS, since its reception will enable the transmission of Data, we should also preventing it from colliding. I think that is the main idea in DBTMA, i.e., protecting CTS and Data.

Subject: RE: [manet] Carrier sense threshold/range control  
Date: Fri, 11 Jul 2003 10:54:51 +0800  
From: "#LI ZHIFEI#" <zhifeili@pmail.ntu.edu.sg>

>>probability (distance between nodes > 2SR) =< probability (distance between nodes > SR ).

If you mean that (distance between nodes > 2TR) =< probability (distance between nodes > TR ), this may not be the case in the multi-hop wireless ad hoc networks. Of course, your statement should be held in the WLAN or single-hop ad hoc networks.

> Though we may not be eliminating all the hidden terminals but we may decrease the probability of occurrence of hidden terminals by extending sensing range to 2SR.       ???? >2TR

The objective of eliminating the hidden terminal problem is to reduce collisions and thus increase the channel utilization. However, if you increase the sensing range, the interfering range is also increased and thus the spatial reuse is greatly reduced. Of course, if capture is enabled, it may be a different story. However, with capture, fairness becomes worse (which is my main concern). Moreover, as I have mentioned, when the sensing range (SR) is made greater than transmission range (TR), how long a node should defer its transmission when it detects a SR frame is a very difficult job as the node cannot interpret the content of a SR frame.

Li zhifei

Subject: RE: [manet] Carrier sense threshold/range control  
Date: Fri, 11 Jul 2003 00:08:47 -0400  
From: "Chi-Hsiang Yeh" <chi-hsiang.yeh@ece.queensu.ca>

Hi, Zhifei,

>> Though we may not be eliminating all the hidden terminals but we may decrease the probability of occurrence of hidden terminals by extending sensing range to 2SR.       ???? >2TR

>

> The objective of eliminating the hidden terminal problem is to reduce collisions and thus increase the channel utilization. However, if you increase the sensing range, the interfering range is also increased and thus the spatial reuse is greatly reduced.

This is not true. Besides SR and TR, there is another parameter "interference range (IR)", which is not necessarily equal to SR. By lowering the threshold for sensing, increasing SR does not affect IR. Instead, IR is increased when the associated transmission power level is increased.

Also, when  $SR \geq IR + TR$ , topology 2 (in your previous e-mail) and other topologies without obstacles would not suffer from the hidden terminal problem (without considering collisions of control messages and propagation characteristics/delays etc. of course).

Chihsiang

Subject: RE: [manet] Re: Carrier sense threshold/range control  
Date: Fri, 11 Jul 2003 02:51:41 -0400  
From: "Chi-Hsiang Yeh" <chi-hsiang.yeh@ece.queensu.ca>

Another problem: When C is close to B and C is really a transmitter (rather than being mistaken due to typos in the original e-mail), the data reception at B will be collided by the data transmission from C even if the above dialogues work due to capture.

Chihsiang

Subject: RE: [manet] Carrier sense threshold/range control  
Date: Fri, 11 Jul 2003 16:12:30 +0800  
From: "#LI ZHIFEI#" <zhifeili@pmail.ntu.edu.sg>

Is there any formal definition about the "interference range"? The definition of "interference range" in the following paper is some confusing to me.

How effective is the IEEE 802.11 RTS/CTS handshake in ad hoc networks?

Kaixin Xu; Gerla, M.; Sang Bae; Global Telecommunications Conference, 2002. GLOBECOM '02. IEEE , Volume: 1 , Nov 17-21, 2002 Page(s): 72 -76

However, I do believe that when SR is increased, the spatial reuse in multi-hop networks will be substantially reduced, which is also pointed out in the above paper.

Best regards  
Li ZhiFei

Subject: RE: [manet] Carrier sense threshold/range control  
Date: Fri, 11 Jul 2003 16:44:33 +0800  
From: "#LI ZHIFEI#" <zhifeili@pmail.ntu.edu.sg>

>Also, when  $SR \geq IR + TR$ , topology 2 (in your previous e-mail) and other topologies without obstacles would not suffer from the hidden terminal problem (without considering collisions of control messages and propagation characteristics/delays etc. of course).

That is true but at the cost of capacity. Moreover, if  $SR \geq IR + TR$ , it seems that the RTS/CTS do not have much meaning any more. However, as pointed out by some work, whether the SR can be set to greater than  $(IR + TR)$  depends upon the antenna's sensitivity.

Subject: [manet] Re: Carrier sense threshold/range control  
Date: Fri, 11 Jul 2003 15:41:12 +0530  
From: "Leena Chandran-Wadia" <leena@it.iitb.ac.in>

Dear Dr. Perkins,

- >1. allow node C to transmit to D while B is transmitting a data frame to A
- >2. force C to keep silent just in time for B to receive the ACK from A.
- >
- >This MAY result in better channel utilization but SHOULD require a more
- >complex access/NAV scheme. Any thoughts...

We have tried 1. and 2. on 802.11 ad hoc networks. As mentioned by Nitin Vaidya, packet sizes become important if one wants to allow parallel transmission. C can indeed transmit to D while B is sending data to A, provided it has a packet small enough so that it can finish transmission and be silent in time for B to receive the ACK from A. Also, the transmission from C to D must not use RTS/CTS. C can even receive an ACK from D provided the end of transmission of its data is aligned with that of B.

We have implemented this in GloMoSim - turns out to be not too complex. The details are available in a paper just accepted to ICCCN <http://www.it.iitb.ac.in/~sri/papers/expnode-ic3n03.pdf>

The camera ready version of this paper is due on August 1st. If you and others on the list can offer comments/criticisms, we would be glad to try and incorporate them - at least the ones we can handle in the next 2 weeks...We can also make the implementation available if someone wants to experiment with it.

There is also another effort in this direction. The authors have a much more complex algorithm, called MACA-P, which involves negotiations between pairs of transmitting nodes. There is an IBM research report (RC 22528) somewhere in cyberspace. The paper was presented at IEEE PerCom 2003.

Thanks,  
Leena

Subject: RE: [manet] Carrier sense threshold/range control  
Date: Fri, 11 Jul 2003 12:36:16 -0400  
From: "Chi-Hsiang Yeh" <chi-hsiang.yeh@ece.queensu.ca>

> That is true but at the cost of capacity. Moreover, if  $SR \geq IR + TR$ , it seems that the RTS/CTS do not have much meaning  
> any more.

You are right, for free space. For indoor environments, strategies using large SR alone do not work well due to obstacles. If anyone has or know experiments on this issue (indoor + large SR), I'll appreciate it if you could give me a pointer.

> However, as pointed out by some work, whether the SR can be set to greater than  $(IR + TR)$  depends upon the antenna's sensitivity.

You are right. And it also depends on path loss etc. There is always a limit on SR, and in reality it may not be easy to know these parameter values directly or to make  $SR=IR+TR$ .

Chihsiang

Subject: Re: [manet] Carrier sense threshold/range control  
Date: Fri, 11 Jul 2003 09:54:55 -0700  
From: "Alaa Muqattash" <alaa@ece.arizona.edu>

Could you please explain what do you mean by the "interference range"? I don't think that this range is fixed. Instead, it depends on:

- 1- The transmission power
- 2- The channel gain between the transmitter & receiver
- 3- The minimum SNR threshold required for reliable communication

For example, fixing all other parameters, if the required SNR is increased, then your interference range is increased.  
Any thoughts?

regards,  
Alaa

Subject: RE: [manet] Carrier sense threshold/range control  
Date: Fri, 11 Jul 2003 11:49:37 -0600  
From: "John Mullen" <jomullen@nmsu.edu>

Hi Alaa,

As I use it, the IR is the distance at which a transmitted signal from a terminal interferes with that of another at the receiver. You are correct in that the distance is not fixed. If A is sending to B in the presence of a signal from C, whether or not B can successfully decode A's transmission depends on the signal strength from A, that from C, and the noise level at B.

A simple approximation is to treat the transmission from C as noise and to look at the ratio of  $SN(A) / [SN(C)+N]$ . However, this is inexact. Because C's signal is actually a valid transmission, it would be more difficult for the receiver to ignore. (I'm assuming C is using the same channel, waveform, etc. as A and B).

To illustrate, if you had a signal from C that was just marginally rejectable by B, reducing A's signal strength, by any means, e.g. antenna gain, distance, xmitter power, etc., would cause that signal to cause a data collision at B. On the other hand, if the signal from A increases, then that of C would become less and less significant.

I think most people consider the IR to that which would cause interference at an extreme A-B range, but this is misleading in that when A&B are closer, the interference source can also be closer without causing difficulty.

John Mullen

Subject: RE: [manet] Carrier sense threshold/range control  
Date: Fri, 11 Jul 2003 16:31:04 -0400  
From: "Chi-Hsiang Yeh" <chi-hsiang.yeh@ece.queensu.ca>

Hi, Alaa,

The Globecom'02 paper of Xu, Gerla, and Bae defined interference range as "the range within which stations in receive mode will be "interfered with" by an unrelated transmitter and thus suffer a loss."

This paper assumes that wireless stations are transmitting at a fixed power level, using the same modulation etc...

I myself usually assume that there is a minimum interference threshold every receiver needs to be able to tolerate, where the resultant collision probability is sufficiently small when the cumulative interference is smaller than that threshold. If you have lower gain or need higher SINR, the associated transmitter needs to transmit at a power level that is sufficiently high. I call a related parameter "maximum interfered range". This value is fixed for a certain transmission, but different transmissions have different values. For a receiver, there is another parameter "maximum interfering range". My protocols need them to determine the power levels for transmitting RTS and CTS messages respectively.

You may also look at

J. L. Sobrinho and A. S. Krishnakumar, "Quality-of-Service in ad hoc carrier sense multiple access networks," IEEE Journal on Selected Areas in Communications, 17(8), August 1999, pp. 1353-1368.

Regards,  
Chihsiang

Subject: RE: [manet] Carrier sense threshold/range control  
Date: Fri, 11 Jul 2003 16:53:33 -0400  
From: "Chi-Hsiang Yeh" <chi-hsiang.yeh@ece.queensu.ca>

Hi, Zhifei,

> However, I do believe that when SR is increased, the spatial reuse in multi-hop networks will be substantially reduced, which is also pointed out in the above paper.

You are right when SR is too large so that CSMA becomes too conservative (and the exposed terminal problem deteriorates). But such reduction in throughput is not caused by increase in IR (and in fact IR is not increased in such a case).  $SR \geq IR + TR$  is just a condition to solve the hidden terminal problem in open space (as I was pointing out that this was possible when there were no obstacles). It is not necessarily a condition optimized for throughput, collision rate, or other metrics.

Best regards,  
Chihsiang