Revisiting Distributed Transmit Power Control in Ad Hoc Wireless Networks with ODC Capability

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***Abstract*—With a view to conserve energy, a basic power control (BPC) scheme was suggested in distributed control IEEE 802.11 wireless ad hoc networks, where a data frame is sent at the lowest permitted power. Past research showed that BPC works inefficiently in terms of throughput as well as energy consumption. In this paper we revisit the effects of BPC on the network performance with the nodes having frame arrival order dependent signal capture (ODC) capability. We first analyze the reasons for poor performance of basic power control without ODC. We then investigate the effect of ODC on system throughput as well as energy efficiency. Via intuitive arguments and network simulations we demonstrate that, in presence of ODC capability of the receivers, BPC can be highly effective in terms of throughput as well as energy efficiency.**

Index Terms – Carrier sense multiple access, order dependent capture, distributed power control.

I. Introduction

Energy conservation in wireless ad hoc networks is crucial. Besides increasing the effective ON-time of a battery operated device, frugal energy usage also leads to *green networking* [1]. With a view to reduce power consumption, a simple power control scheme (called basic power control or BPC) was proposed [2], [3] in distributed control IEEE 802.11 wireless ad hoc networks that use the request-to-send (RTS) / clear-to-send (CTS) access mechanism. In BPC, RTS and CTS are sent with maximum permissible power and the subsequent data and ACK frames are exchanged with a minimum power required to sustain the communication between the sender-receiver (S-R) pair. This scheme works fine as long as all the potential interferers are located within the transmission range of either sender or receiver. However, this condition is not valid even for a moderately large S-R distance, when the use of RTS/CTS exchange is no longer sufficient in mitigating *hidden terminals* problem [4]. With BPC, the situation becomes worse, since the signal-to-interference ratio (SIR) for the data frame is severely degraded due to substantial reduction in received signal power while the interference power remains unchanged. Past research works [5], [6] have shown that the performance of the network is significantly poor in terms of both throughput and energy efficiency when BPC is employed.

Recent experimental results based on real hardware test-bed studies [7]–[10] have shown that the minimum SIR (a.k.a. capture threshold δ) required for successful reception of a signal frame is dependent on the order in which the overlapping frames arrive. Particularly at low data rates (up to 18 Mbps), the value of δ is substantially lower when the signal frame arrives earlier than the interference frame. This order dependent capture (ODC) capability is exploited at medium access layer (MAC) and the resulting performance has been investigated by different researchers [9], [11]–[14]. However, to the best of our knowledge the impact of ODC on power control issues has yet not been investigated.

In this paper, we reevaluate the performance of BPC in light of ODC. Through analysis, supported by network simulation studies, we confirm the significantly poor performance of BPC over WPC (without power control), in terms of throughput as well as energy efficiency, when ODC is not considered. Our further studies show that the BPC proves to be very effective if used in conjunction with ODC. Particularly, with the ODC capable nodes the throughput of network with BPC does not degrade while the energy consumption is reduced by a factor of 3.5 as compared to WPC case.

The rest of the paper is organized as follows: After a brief overview of some preliminaries, Section II analytically investigates the reasons for the poor performance of BPC without ODC by accounting the effects of S-R distance and different nodal ranges. How the performance of BPC improves with ODC is explained in Section III. Simulation results are discussed in Section IV. Section V concludes the paper.

II. Ineffectiveness of Basic Power Control Scheme

In this Section, through the concepts of nodal transmission range, carrier sensing range, and interference range, we note that the reason of poor performance of BPC is highly increased interference zone. Subsequently, we justify via analytic arguments that the interference problem can be mitigated by exploiting ODC.

A. Different Nodal Ranges

Following the standard path loss model [15] the received signal strength P_r at a receiver R can be given as

$$P_r = P_0 \left(\frac{d_0}{d_{SR}}\right)^{\alpha} \tag{1}$$

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where P_0 is the received signal strength measured at a reference distance d_0 from the sender S, d_{SR} is the S-R distance, and α is the path loss exponent (typically, $2 \le \alpha \le 4$).

Let Γ_t be the minimum power level required for successful decoding of a received frame. The distance from the transmitter where the received signal strength equals Γ_t is called the transmission range R_t. Using (1), it can be given as

$$R_t = d_0 \left(\frac{P_0}{\Gamma_t} \right)^{\frac{1}{\alpha}} \tag{2}$$

Besides Γ_t, each node also uses another threshold called carrier sense threshold Γ_c for implementing the CS part in *carrier sense multiple access* (CSMA) mechanism. When the sensed power level is above Γ_c, the medium is identified as busy and a transmission aspirant node defers its own transmission [16]. This leads to a definition of carrier sensing range R_c around the transmitter serving as a minimum distance between two permitted concurrent transmissions. From (1),

$$R_c = d_0 \left(\frac{P_0}{\Gamma_c} \right)^{\frac{1}{\alpha}} \tag{3}$$

Since P_0 is proportional to the transmit power P_T, R_t and R_c are the functions of P_T as well as the respective thresholds.

For a successful frame reception, the signal-to-interference ratio (SIR) at a receiver R should be above a capture threshold δ. Let P_s and P_i respectively be the signal strengths with which a signal frame from sender S and an interference frame from interferer I arrive at receiver R. Then, from (1) the minimum SIR condition can be given as

$$\frac{P_s}{P_i} = \frac{P_0^S}{P_0^I} \left(\frac{d_{RI}}{d_{RS}} \right)^{\alpha} \ge \delta \tag{4}$$

where the superscripts (S or I) used with P_0 take care of the possibility of different transmit powers being used for the involved signal and interference frames.

The condition in (4) gives the interference range R_i as:

$$R_i = \left(\frac{\delta P_0^I}{P_0^S} \right)^{\frac{1}{\alpha}} .d_{RS} \tag{5}$$

In case of WPC, when all (data and control) frames are transmitted at the same power, the expression (5) reduces to

$$R_{i_{WPC}} = (\delta)^{\frac{1}{\alpha}} d_{RS} = K.d_{RS} \tag{6}$$

where $K \triangleq \delta^{\frac{1}{\alpha}}$. Thus, R_i is directly proportional to the S-R distance and is maximum when $d_{RS} = R_t$.

When one employs virtual carrier sensing (VCS) [16], all the potential interferers that are located inside R_t of either the sender of the receiver will know the duration of subsequent data-ACK exchange, and hence they will defer their own transmission till then. In other words, VCS is effective in mitigating interference within the transmission range of sender and receiver. Further, from the discussion about R_c in (3), it is clear that all the potential interferers that are located within R_c of the sender would be continuously sensing the data frame being transmitted and hence (following CSMA/CA protocol), will not initiate their own transmission.

In a nutshell, those nodes that are within R_i of a receiver but covered by neither physical carrier sensing (PCS) (i.e., outside R_c of sender) nor VCS (i.e., outside R_t of sender or receiver) will remain as *hidden terminals* causing interference. The dark shaded zone in Fig. 1 is the interference zone for a data frame reception at node R for WPC case.

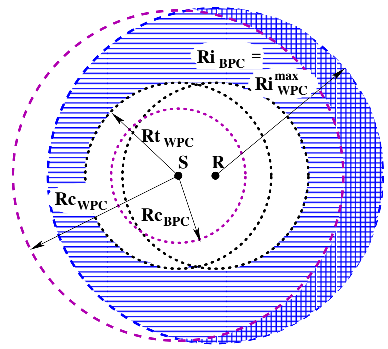

Fig. 1. Reduction in $R_{c_{BPC}}$ increases the area of hidden zone. The complete shaded region is hidden for the data frame received at R. The larger the S-R distance, the smaller this region, which gradually shrinks to just the dark shaded zone when S-R distance equals R_t.

B. Basic Power Control Scheme with and without ODC

In BPC, when by using maximum power RTS/CTS have already reserved the medium, it should be safe to reduce the transmission power for the subsequent data and ACK frames to a level that is just sufficient to successfully receive the frame (i.e., received power $\approx \Gamma_t$). The reduction of received signal power to its minimum possible value and the fact that the interfering frame (which could be an RTS) could be transmitted with maximum power, the minimum SIR requirements in (4) results in an interference range around a receiver given as:

$$R_{i_{BPC}} = K.R_t = R_{i_{WPC}}^{max} \tag{7}$$

Further, the reduction in transmit power reduces the CS range R_c around the data frame sender. As the values of the two thresholds Γ_t and Γ_c are not changed, the value of R_c for BPC (during data transmission) becomes a function of the S-R distance, given as

$$R_{c_{BPC}} = K' d_{SR}, \quad \text{where } K' = \left(\frac{\Gamma_t}{\Gamma_c} \right)^{\frac{1}{\alpha}} \tag{8}$$

From (7) and (8), and from the concept of hidden interference discussed above, it is clear that, for BPC scheme the interference zone around receiver is significantly increased for small values of S-R distance. The complete shaded region in Fig. 1 shows the interference zone for BPC.

Different from the conventional exposed terminals zone, we define *transmission deferral* zone as the region in which a node is prevented from transmission by an on-going transmission of a data frame. Clearly, besides covering the nodes within R_c radius of the sender, this zone also covers the nodes within R_t radius of the sender as well as that of the receiver. Obviously, the more the area of this zone the lesser the spatial reuse.

The areas of interference and transmission deferral zones are plotted for WPC and BPC in Fig. 2 as functions of S-R distance d_{SR} with typical values of R_t, δ, and R_c. Note

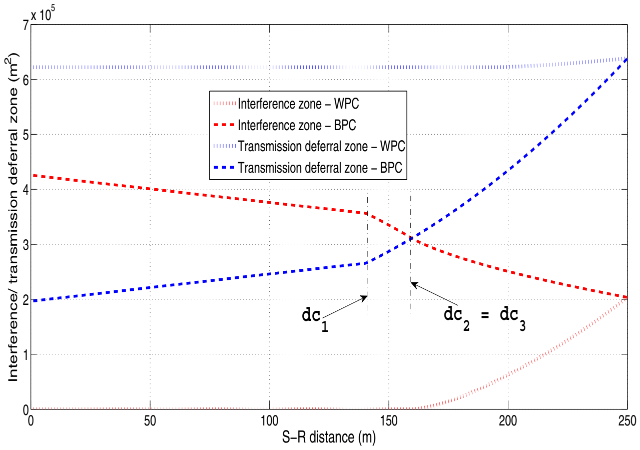

Fig. 2. Variation of interference and transmission deferral zones in BPC and WPC schemes. $R_t = 250$ m, $\delta = 10$ dB, and $R_c = R_i^{max} = 445$ m.

that, the interference region in BPC shrinks gradually with the d_{SR} to finally become equal to its counter part in WPC at $d_{SR} = R_t$. This suggests a corresponding improvement in the performance of BPC with S-R distance. On the other hand, the transmission deferral zone for BPC increases towards that of WPC case in a fashion complementary to the trend of interference zone variation. This suggests a corresponding reduction in the performance of BPC with S-R distance.

For WPC case, when $R_c \geq d_{SR} + R_{i_{WPC}}$, all the interferers of a data frame are covered by PCS. Thus, using the value of $R_{i_{WPC}}$ in (6) we have, $d_{c_2} = \frac{R_c}{K+1}$ (~ 160 m), below which the interference zone in WPC is nil. On the other hand, the transmission deferral zone is constant up to $d_{SR} = R_c - R_t$ ($= 195$ m), mainly determined by the complete circular region of radius R_c around S. Beyond that distance, it increases slightly due to an additional portion of the zone of R_t radius around R getting outside that of radius R_c around S. This suggests that, up to d_{c_2}, the performance of WPC should be constant, mainly determined by the available spatial reuse. Beyond d_{c_2}, the performance should gradually reduce on account of increased interference.

III. Improved Performance of BPC with ODC

ODC leads to two values of δ: one for the case when intended signal frame arrives earlier than the interference (a.k.a. **S**ender's **F**irst or SF case) and another for the case when the order of arrival reverses (a.k.a. **S**ender's **L**ast or SL case). At low rate operations ($= 6$ Mbps), $\delta^{SF} = 0$ dB [7], [10] and hence from (6) and (7) we have,

$$R_{i_{WPC}}^{SF} = d_{SR} \text{ in WPC} \quad (9)$$

$$R_{i_{BPC}}^{SF} = R_t \text{ in BPC}. \quad (10)$$

As the value of δ^{SL} remains high, R_i for SL overlaps (in WPC as well as BPC) remains comparable to the R_i without ODC. However, the prior transmission of RTS/CTS with maximum power prevents almost all SL overlaps with a data frame [12]. Therefore, the vulnerability of data frames with ODC is limited mainly to SF overlaps. From (9) and (10), all such interferers are located within the R_t range of R where VCS is effective. For any S-R distance, this phenomenon reduces the interference to a data frame with ODC. Note that, the performance gain with ODC is mainly due to reduced interference, as the transmission deferral zone is not affected by it.

IV. Network Performance Results and Discussion

We have verified our analytic observations via simulation experiments in ns2 [17]. The software was modified to incorporate the ODC and power control mechanisms. We have evaluated the following four cases: 'WPC without/with ODC' and 'BPC without/with ODC'. The performance metrics are per-flow end-to-end throughput (bps), and energy efficiency or total energy consumed in transmission and reception per unit data transfer (joules/bit). Two types of network scenarios are tested: S-R distance dependent performance, and the effects of forwarding protocol in a more realistic multi-hop network. In both the scenarios, 802.11a MAC protocol is realized at 6 Mbps data rate. Each flow is constant bit rate (CBR) over UDP with 1 Mbps offered data rate. Log distance propagation model is used with $\alpha = 4$. The nodal parameters are set as: $R_t = 250$ m, $R_c = 445$ m [12], $\delta^{SL} = 10$ dB, $\delta^{SF} = 0$ dB [7]. Total simulation time with a seed value was 10 seconds and each point in plots is an average of 35 different seeds.

A. *Effect of S-R distance*

To verify our observations in Section II-B, we set up a network with 40 S-R pairs randomly deployed in 1250×1250 m^2 area. d_{SR} for each pair was kept in the range of $[0, R_t]$. 20 S-R pairs were randomly chosen for data transmissions.

Figs. 3 and 4 show the average per-flow throughput and energy efficiency for different values of S-R distances. It can be observed that, the throughput performance of 'BPC without ODC' is substantially lower than the other three cases, and it gradually merges with that of 'WPC without ODC' when $d_{SR} = R_t$. This effect is mainly due to a substantially higher interference in 'BPC without ODC' for any value of d_{SR}. The shape of the plots for 'BPC without ODC' (throughput as well as energy efficiency) is in line with the observations from Fig. 2. As noted earlier (while deriving (8)), $R_{c_{BPC}}$ increases with d_{SR}. In the region at lower values of S-R distances, $R_{c_{BPC}} \leq$

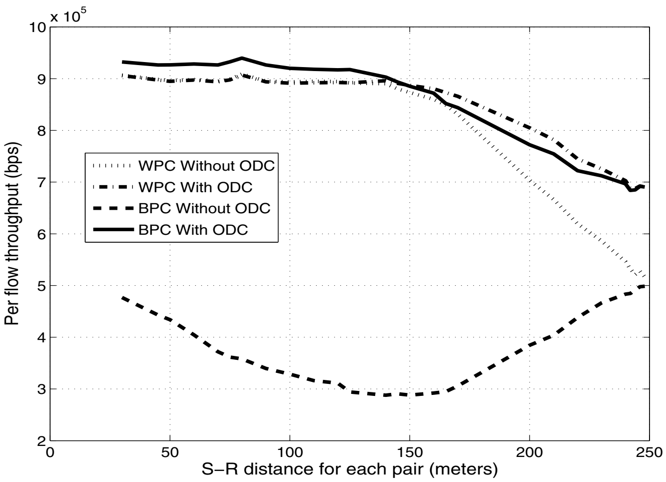

Fig. 3. Throughput versus S-R distance.

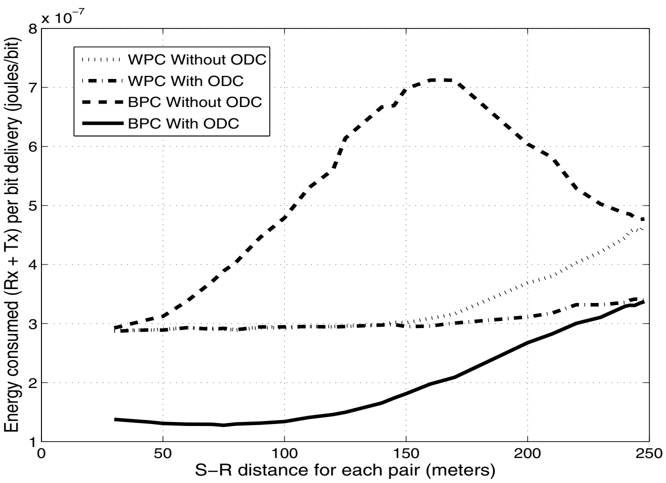

Fig. 4. Energy efficiency versus S-R distance.

R_t, which corresponds to $d_{SR} \leq dc_1 = \frac{R_t}{R_c/R_t}$ (~ 140 m). In this region, throughput reduces with the increase in distance implying the determining factor to be the spatial reuse. When d_{SR} increases beyond $dc_3 = \left(\frac{K}{(R_c/R_t)+1}\right) R_t$ (~ 160 m) such that $R_{c_{BPC}} + d_{SR} > R_{i_{BPC}}$, the performance improves (at a relatively higher rate), gradually merging with that of WPC. This indicates that, after dc_3, which is incidentally same as dc_2 for the chosen value of $R_c = K.R_t$ [12], the performance is mainly determined by the amount of interference.

Similarly, the performance of WPC is constant up to dc_3 and then degrades, however at a slower rate with ODC capability due to its reduced vulnerability to interference. Though the throughput performance of 'BPC with ODC' is almost at par with 'WPC with ODC', the energy saving of 'BPC with ODC' is substantially better as observed in Fig. 4.

B. Effect of forwarding strategies

In the second scenario, 80 nodes are randomly deployed in 1250×1250 m^2 area. Total 10 flows are randomly established such that the end-to-end source-destination distance is in the range [500 m, 600 m]. With $R_t = 250$ m, this average flow distance corresponds to 3 to 4 hops, when a greedy forwarding protocol (like greedy perimeter stateless routing or GPSR) is used. Figs. 5 and 6 show the throughput and energy efficiency with GPSR.

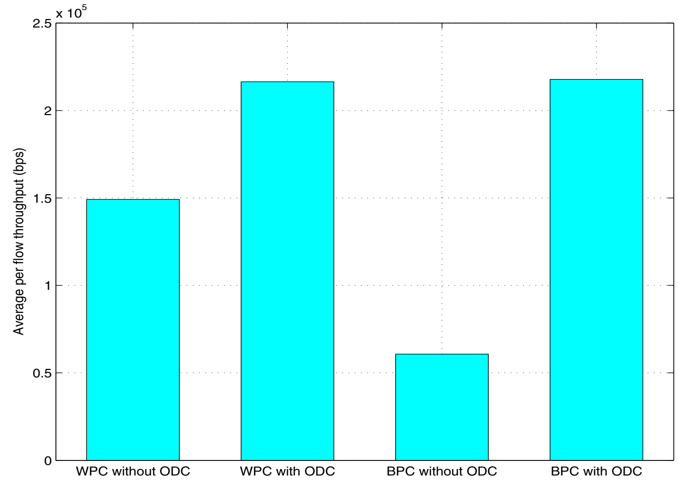

Fig. 5. Throughput performance in a random multi-hop network with 10 flows. GPSR is used as underlying routing protocol.

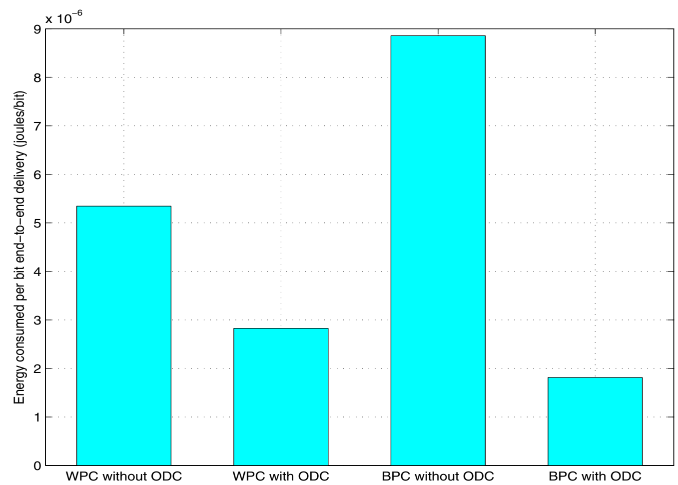

Fig. 6. Energy efficiency in a random multi-hop network with 10 flows. GPSR is used as underlying routing protocol.

An alternative location aware forwarding protocol, called nearest forward progress (NFP) [18], is also considered for performance comparison. Figs. 7 and 8 show the corresponding throughput and energy efficiency results. In general, all the plots confirm the poor performance of 'BPC without ODC' as compared to 'WPC without ODC'. The degradation in throughput performance as well as in energy efficiency is about 2 times and 10 times for GPSR and NFP, respectively. The reason for this difference is due to smaller average one-hop S-R distance in case of NFP where the hidden interference region

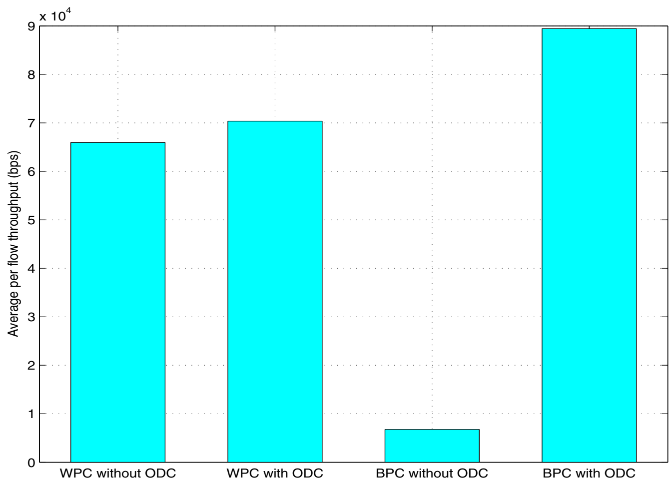

Fig. 7. Throughput performance in a random multi-hop network with 10 flows. NFP strategy is used at network layer.

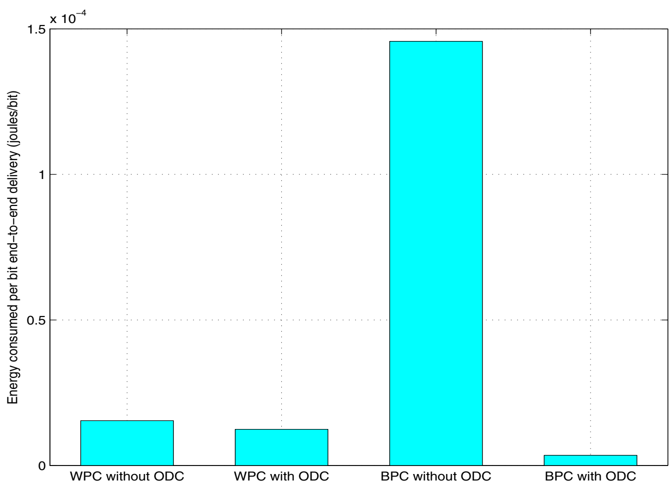

Fig. 8. Energy efficiency in a random multi-hop network with 10 flows. NFP strategy is used at network layer.

in a power controlled transmission is quite large. The increased loss of packets leads to increased number of retransmissions leading to a poor energy efficiency.

The throughput performance of 'BPC with ODC' is almost comparable to that of 'WPC with ODC' for GPSR and better in case of NFP. So far as energy efficiency is concerned, 'BPC with ODC' is found to be quite effective. The energy saving with respect to 'WPC with ODC' is around 27% when using GPSR and around 250% with NFP.

V. Conclusion

In modern wireless cards the capture threshold depends on the order of arrival of overlapping frames. Without considering this order dependent capture (ODC), prior research works had shown the basic power control scheme to be ineffective in terms of throughput as well as energy efficiency. In this paper, we have investigated the reasons for this poor performance as a function of sender-to-receiver distance, transmission range, carrier sense range, and interference range. We have shown why the consideration of ODC improves the performance of the simple power control scheme. Through extensive simulations we have demonstrated that, the basic power control scheme is highly effective in terms of throughput as well as energy efficiency when ODC is exploited.

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