A NOVEL LOAD-SHARING ALGORITHM FOR ENERGY EFFICIENT MAC PROTOCOL COMPLIANT WITH 802.11 WLAN

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ABSTRACT

In this paper, we propose a new method for energy saving to transfer packet data in a wireless local area network (WLAN). The core of this method is based on load sharing. For this reason, we propose a mathematical framework for minimizing power dissipation when transferring MAC (medium access control) protocol data unit (MPDU) using CSMA/CA. Further, we present a load-sharing algorithm enabling energy efficient transfer of MPDU. Finally we implement the algorithm considering a typical scenario for WLAN system using 802.11 specification and Direct Sequence Spread Spectrum (DSSS) at the physical layer. The extensive simulation results show that power reduction of the excess power is 10-50% resulting in total power saving from $5 - 15\%$.

1. INTRODUCTION

Wireless Local Area Network (WLAN) gained a lot of interest during the recent years. Its superiority comparing to the wired LAN is the mobility, easy to maintain and install. As a result a working group under the Institute of Electrical and Electronics Engineers (IEEE), known as IEEE 802.11 was formed in order to promote a standard ensuring interoperable products for WLAN [3][1].

For wireless connectivity of the mobile device, known as mobile station, henceforth referred to as *STA*, the IEEE 802.11 supports two types of networks: *ad hoc* known as *independent basic service set (IBSS)*and *client server architecture* [3]. In the client server architecture, STA communicate through the AP (Access Point). The AP is characterized by its coverage area known as *BSA* (Basic service area). The ensemble BSA and its associated STAs are called Basic Service Set (BSS). The AP contains the same layers as the STA, i.e. PHY and MAC layers and provides access to the distribution services for its associated STAs. However, as opposed to the mobile STA, the power supply used by AP is not limited by the capacity of the battery. Thus, besides the limited bandwidth and the high-cost, the bottleneck for designing WLAN system is the power efficiency. Because the amount of energy, for the mobile STA, is limited by the capacity of the battery and it was estimated that battery capacity will increase by approximately 30% in the next 5 years[11]. Thus "low-power" design has became a key parameter for VLSI circuit design used in mobile applications [4]. Current VLSI circuit is made using CMOS process (both analog and most of the RF part). It has been proven that by selecting a low-complex, highly pipelined algorithm, and an energy efficient architecture, implementing functionality at different OSI (Open System Interconnect) layers, a several order of magnitude for power saving was achieved. Therefore, many of the algorithmic research was shifted towards designing low-complex high performance hardware oriented algorithm [15] [2]. Recently several researchers proved that a substantial power saving (up to 70%) can be achieved by designing energy efficient protocol [6]. Thus many of the techniques enabling energy efficient protocols were proposed and reported in the literature [7]. Those techniques were based on adaptive packet length selection, adaptive coding and modulation, reducing the number of hops in multi-hop system [6]. In this paper, by studying the CSMA/CA protocol, which is supported by *IEEE 802.11* standardization unit for WLAN, we propose a very effective way for power saving at the MAC layer using load sharing. In our analysis we consider the case of basic access method in client-server architecture using Distribute Coordination Function(DCF)[3]. However, we believe that it can be generalized for other class of multiple access protocol.

This paper is organized as follows: in section 2 we describe CSMA/CA. In section 3 we give the mathematical framework for minimizing energy at the MAC layer, and we derive the load-sharing algorithm. Section 4 shows the experimental results. Finally we give our conclusions in section 5.

2. CSMA/CA

CSMA is a family of random access protocol [12] where a number of users content for medium access. The most popular CSMA protocol is the one used by Ethernet protocol (802.3), and it is called CSMA/CD (Carrier Sensing Multiple Access with Collision Detection). However, in the wireless network a given transmitter, cannot detect the collision by listening to its transmission, thus 802.11 supports a modified version of CSMA/CD called CSMA/CA. In the CSMA/CA MAC protocol know as Distributed Coordination Function (DCF), which, according to [3], is a class of coordination function (CF) where the same logic CF logic is active in every STA in a given BSS, whenever the network is operational. In other words, there is no "central"coordination function controling the way each member of the BSS accesses to the Wireless Medium (WM). DCF is based on CSMA/CA protocol. In CSMA, basic access method, the STA senses the channel. If it is idle then initiates transmission and waits for an acknowledgement (ACK) from

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the AP. At the case the channel is busy, the STA selects a random backoff time (random slot) and enters in contention mode (backoff state). In the backoff state, the mobile decrements its backoff timer every time senses an idle slot. However, if the STA is in backoff state and senses the channel busy, the value of its backoff timer is frozen, and the "count-down" presumes after it senses the channel idle for more than DIFS (Distributed Inter-frame Space). The STA, in backoff state, transmits its packet only and only if the value of its backoff timer reaches zero. If STA did not receive an ACK as a response to its transmitted packet (either because the packet did not correctly reached the AP, or the ACK sent by the AP was not successfully received by the STA), the STA concludes that its packet was collided and selects a random backoff time, after sensing the channel is idle for a period more or equal to DIFS. The value of backoff timer is exponentially increased each time the collided packet collides again. The integer value of the backoff timer or CW is selected (randomly) from the interval $[CW_{min}, CW_{max}]$. At the case $CW = CW_{max}$ it remains at that value as long as the current retransmitted packet was not successfully transmitted. In some application, the number of retransmission per packet (R_{max}) is limited. Therefore, if a given retransmitted packet reaches it maximum allowed retransmission (R_{max}), then MAC reports to its upper layer that a failure occurred when transmitting the current packet, remove it from its current buffer and commence the transmission of the remaining packets.

For a given STA associated with an AP, the successful transmission of a given packet holds if the following requirements are satisfied[8]:

1. Neither "stronger" stations nor hidden terminals to the current STA initiates a transmission in the time interval (t-β,t+β), where β is the propagation delay normalized by the average length of the exchanged MAC packet.
2. No "hidden station" to the current STA initiates transmission in the interval (t+l+DIFS, t+l+max$\{DIFS, SIFS + l_{ack}\}$, where l_{ack} is the time need to transmit an ACK packet, SIFS is the length of the Short InterFrame Space.

Thus for a given packet $m_{k=1\ldots M}$, the probability (lower bound [8]) of successfully transmission of the packet m_k,$p_s(i)^{m_k}$, is given by eq.1

$$p_s(i)^{m_k} = \exp(-\beta \sum_{m \in C_i} G(m) - \\ max\{0, SIFS + l_{ack} - DIFS\} \sum_{h \in H_i} G(h)), \quad (1)$$

where C_i is the number of mobiles in the capture area of the station STA_i excluding the hidden terminals to the STA_i[8];H_i is the hidden terminals to STA_i. Using eq.1, the throughput from STA_i to the AP is given by eq.2

$$S(i) = \frac{p_s(i) \times [G(i) + (1 - \exp(-\beta \times G(i))) \sum_{m \in C_i} G(m)]}{1 + G(l + DIFS + l_{ack} + SIFS)} \quad (2)$$

where $p_s(i) = \frac{\sum_{k=1}^{M} p_s(i)^{m_k}}{M}$. The system throuput is given by eq.3

$$S = \sum_i S(i) \quad (3)$$

From eq.2, eq.1 and eq.3 it is easy to see that $S(i)$,S and $p_s(i)^{m_k}$ decreases if p_h (probability of hidden terminal) increases, or N (number of STA or load)increases. The capture or "near-far" increases if N increases, and it depends on the spatial distribution of the users. It was proved that at a given instant of time t the probability $p_{f,t}$, that some other users selects the same slot as the mobile under consideration is given by eq.4[10]

$$p_{f,t} = \sum_{m=1}^{N} [C_m^N (1 - \exp(-G(m))^m \\ \times \exp(-G(m))^{N-m} \times [1 - \frac{K-1}{K}^m], \quad (4)$$

where K is the size of the CW window, K=255 for the case of 802.11.

Suppose that the power need to retransmit a collided packet is γ times less than the power needed to transmit a non-collided packet(P_{min}). Then P_t dissipated by the STA to transfer M MAC layer packet (MSDU) is: $P_t = M \times P_{min} \times (1 + \gamma p_s(i))$. Ideally (in collision free system), $P_t = M \times P_{min}$. The quantity $\eta_i = \gamma p_s(i) \times M \times P_{min}$ is the "excess" power due to the collisions. Therefore, at a given instant of time, t, minimizing P_t for a given user STA_i is possible only and only if the quantity η_i can be made arbitrary small. η_i depends on the load, hidden terminal and the "near-far' problem (spatial distribution of the STA in the BSA).

3. LOAD SHARING ALGORITHM

3.1. Problem formulation

Let, at a given instant of time t, a number of STA (N_i) associated with an AP (B_i). B_i has a basic coverage area denoted by A_i, where it is assumed to be circular with radius R_i. The STAs are assumed to be randomly distributed, following a given spatial distribution function, in the area A_i, each $STA_{i=1\ldots N_j}$ has a number of arrivals following Poisson process with average of λ packet/sec and average length T. In the remaining paper, we assume that all the users have the same arrivals and the packet length is constant. For a given $STA_{j=1\ldots N_i}$, we aim to reduce the energy dissipation, P_t during a transfer of M MSDUs. It is obvious to see that P_t depends on N_j,the instantaneous status of the link (fading) between AP and STA_i, H_i and C_i. Let n_{AP} the number of APs that partially overlap with B_i, n_{AP} depends on the physical layer used by the AP, E.g. $n_{AP} = 3$ for the case of DSSS or 10 for the case of frequency hopping spread spectrum. Since in this paper we consider DSSS, thus $n_{AP} = 3$. Denoting the APs with partially overlapping area to B_i as $B_{i,1}$ and $B_{i,2}$. At a given instant of time t, B_i $B_{i,1}$ and $B_{i,2}$ experience different number of associated STAs, $N_i N_{i,1}$ and $N_{i,2}$ due to the dynamic nature of the association between AP and a given STA in the same BSS. Thus, at the instant t, it is possible that $N_i > N_{i,1}$ and $N_i > N_{i,1}$. Load sharing is aiming to adjust the load among B_i,$B_{i,1}$,$B_{i,2}$ such that the collision in the area A_i is reduced. Fig.1 shows the scenario for load sharing when $n_{AP2} = 2$.

3.2. Load sharing for energy efficient MAC protocol

In this model we consider a randomly distributed STA $STA_{i=1\ldots N_j}$, where N_j is the load of the B_j, $n_{AP} = 3$. The stations associated to B_j have different quality of services requirements e.g. delay (δ_i), maximum number of retransmission (R_i) per packet. If P_t denotes the power needed to transfer a M packet, the following theorem holds

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Theorem 1 *Let P_{min}: the minimum power to transfer a packet when the channel is idle, in a collision free system, the power to transfer M packet, P_t is bounded, where the upper bound is proportional to the maximum length of the CW.*

Proof 1 *Let P_{min} the minimum power need to transfer a MAC layer packet through the WM. This is the case for an idle channel. Thus there is no "waste" of energy due to "over" sensing the channel. However if the channel is busy, the transmission of the packet occurs after sensing the channel K times. The value of K depends on the value of the contention window (CW) and the status of the WM. Therefore*

$$P_t = P_{min} + \sum_{l=1}^{K} P_{ch}^{l}, \tag{5}$$

where P_{ch}^{l} is the power dissipated due to the l^{th} channel sensing. Let $P_{ch}^{l} = \beta_l P_{min}$, where $0 \leq \beta_l < 1$ eq.5 leads to the following equation

$$P_t = P_{min} \times (1 + \sum_{l=1}^{K} \beta_l) \tag{6}$$

For a given MPDU, the value of P_t depends on the value of K. Since CSMA/CA in 802.11 is designed for time bounded asynchronous transmission, thus $K \in [0 \ldots K_{max}]$. Let P_s^{min} the power dissipated when $CW = CW_{min}$, and P_s^{max} power dissipated when $CW = CW_{max}$. This leads to the relation: $\frac{P_s^{max}}{P_s^{min}} \approx \frac{CW_{max}}{CW_{min}} = \alpha$. Thus $1 \leq \beta_l \leq \alpha$. This leads to the relation $P_{min} \leq P_{min}(1+K) \leq P_t \leq P_{min}(1+K\alpha) \leq P_{min}(1+K_{max}\alpha)$. This gives a bound for P_t.

In the rest of the paper we neglect the overhead due to channel sensing. In [9] an adaptive section for CW was introduced. the adaptation takes into account the estimated number of STA in contention to select the optimum CW such that the throughput is maximized.

Dynamic adjustment of CW reduces the probability $p_{f,t}$ (see eq.4). However the problem of hidden-terminal can't be solved using this techniques, thus a randomly selected $STA_{i=1 \ldots N_j}$ experiences different number of retransmission per packet. Therefore, the power needed to send M MPDU from STA_i to B_j at the instant of time t is given by eq.7

$$P_t = M \times P_{min} + \sum_{l=1}^{N} (\gamma_l \times P_{min}), \tag{7}$$

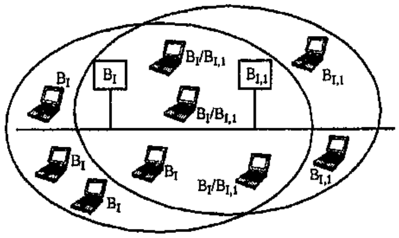

Figure 1: Load sharing scenario

where $0 < \gamma_l < 1$, and P_{min} is the power required to transmit a "new" packet. N is the number of retransmitted packet.

Theorem 2 *Given β: The average number of retransmission/packet and P_{min}: the power for transmitting a new packet, the total power required to transmit M packet using the WM is bounded and its upper limit is $P_{min} \times M \times (1 + \beta \times \gamma_{max})$, where $\gamma_{max} = max\{\gamma_{l=1 \ldots N}\}$*

Proof 2 *From eq.7 and eq.5, one can conclude that $\gamma_{l=1 \ldots N}$ is bounded and it reaches its maximum, $\gamma_{max} = max\{\gamma_{l=1 \ldots N}\}$, thus $0 \leq \gamma \leq \gamma_{max}$ when combined with eq.7 gives the bounds for P_t as:*

$$\begin{aligned} M \times P_{min} \leq P_t &\leq P_{min}(M + N \times \gamma_{max}) \\ &\leq P_{min} M \times (1 + \beta \times \gamma max), \end{aligned} \tag{8}$$

thus at the case if $\gamma_{max} \times \beta \ll 1$ then $P_{M,N}$; $M \times P_{min}$, which is the required power to transfer M packet under zero collision condition.

Theorem 3.2 shows that the number of retransmission per-packet (β)is a bounded discrete stochastic variable. The instantaneous value of β for a given packet $m_{k=1 \ldots M}$ sent by STA $STA_{i=1 \ldots N_j}$ associated with the base station B_j depends on the instantaneous value of $p_s(i)^{m_k}$ (see eq.1), which in turn depends on the instantaneous value of the H_i,C_i and N_j (See condition . 2). In order to reduce H_i, the four way communication (RTS/CTS) can be used, however the penalty for this is the increasing overhead to send M MPDU. The other alternative is to reduce the hidden terminal problem by reassociated the hidden terminal to different APs. This objective is achievable by our load sharing algorithm. In order to be able to derive load sharing algorithm the following theorem is needed.

Theorem 3 *Given N_j: A number of stations (STAs) associated with access point B_j, the average retransmission $\beta_{i=1 \ldots N_j}$ per packet for a given STA_i takes the value x with the probability $p_i\{\beta_i = x\} = \frac{\exp(-\frac{(x-\mu_{B_j,N_j})^2}{2\sigma_{B_j,N_j}^2})}{\sqrt{2\pi}\sigma_{B_j,N_j}}$ where $x \in [0, R_{max}]$, R_{max} is the maximum number of retransmission per packet, μ_{B_j,N_j} is the average number of retransmission/user/packet, σ_{B_j,N_j}^2 is the standard deviation of the number of retransmission/user/packet.*

Proof 3 *Let M consecutive independent packet sent by the STA_i to the AP B_j. For each packet $m_{k=1 \ldots M}$ the probability that is successfully transmitted is $p_s(i)^{m_k}$ (see eq.1) is independent of the status of the previous $m_{1 \ldots k-1}$. As a consequence, the number of retry (retransmission) for packet m_k denoted by $r_k \in [0, R_{mx}]$ is a random variable independent of $r_{1 \ldots k-1}$. Let the variable $\beta_i = \frac{\sum_{k=1}^{M}(r_k)}{M}$ denote the average retransmission per packet for a given STA_i. β_i is a random variable taking value between $[0, R_{max}]$. Assuming $\{r_1, r_2, r_3, \ldots, r_M\}$ are i.i.d RV with mean μ_r and variance $\sigma_{B_j}^2$, then, according to the* Central Limit Theorem*(CLT) β_i is RV with density function $f_x = \frac{\exp(-\frac{(x-\mu_r)^2}{2\sigma^2})}{\sqrt{2\pi\sigma}}$, It is easy to verify that $\sigma^2 = \frac{\sigma_{B_j}^2 + \mu_r(1-M)}{M}$. Since the $STA_{k=1 \ldots N_j}$ associated with B_j are independent and if we further assume $\{\beta_1, \beta_2, \beta_3, \ldots, \beta_{N_j}\}$ are i.i.d then the variable $\beta_{B_j} = \frac{\sum_{i=1}^{N_j} \beta_i}{N_j}$*

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is Gaussian distributed RV (according to the CLT) with mean value: $\mu_{B_j,N_j} = \mu_r$ *and variance* $\sigma^2_{B_j,N_j} = \frac{\sigma^2_{B_j} - \mu_r N_j M}{N_j M}$.

This theorem tells us, that by fixing the average number of collision per user per packet (μ_{B_j,N_j}), the load sharing algorithm used by the highly collided STA associated to B_j for initiating a reassociation process occurs if its estimated average retransmission per packet ($\hat{\mu_r}$) is more than μ_{B_j,N_j}. If we consider the required signal strength (Γ) for a given frame error rate (FER), and the average number of retransmission per user per packet (μ), the proposed load-sharing algorithm is:

1. Estimate the mean value of μ_r denoted by $\hat{\mu_r}$
2. If $\hat{\mu_r} < \mu_r$ then exit
3. Measure the strength of the beacon signal from adjacent APs, $\Gamma_{1 \ldots n_{AP}}$
4. For i=1 to n_{AP} if $BecanPower(i) \geq \Gamma$ get its current load $Load(i)$
5. Ask for reassociation to the strongest adjacent base station having a load less than the load of B_j
6. exit.

4. EXPERIMENTAL RESULTS

In order to measure the performance of the proposed load sharing algorithm, we have implemented a typical scenario where 3 base station A, B and C with overlapping coverage as shown in fig.2. Each station has a MAC layer and it was implemented according to the standard specification. Table.1 gives the parameter used as a configuration for the MAC in our simulation program, which similar to the these used in [16]. In order to model the "near-far" problem, we assume that if, at a given instant of time t, the AP B_j receives packet from n stations: $STA_{k_{1 \ldots n}}$, then the station STA_{k_l} "won" the competition if and only if it is the strongest one satisfying the following inequality $\frac{P_{STA_{k_l}}}{\sum_{k=1 and k \neq l}^{n} P(STA_k)} \geq \Gamma$, where $P_{STA_{k_k}}$ is the received power (at the antenna) due to a packet sent from station STA_{k_k} to B_j. In order to be able to compute the power at the AP, we used the free-space propagation formula for electromagnetic wave, that is the received power $\omega(d)$ of a given electromagnetic wave at a distance d (in meter) with wavelength λ_c is given by eq. 9

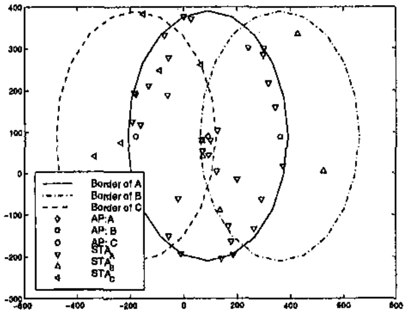

Figure 2: Snapshot of our simulation process, before load sharing

Table 1: Simulation parameter

Packet payload	8184 bits
ACK length	112bits
Channel bitrate	1 Mbit/s
Slot Time	50 μ s
DIFS	128 μs
Freq	2.46 GHz
P_{tx}	100 mW
A_i	30 meter
FER	8×10^{-2}
Γ	0.39 mW
ϵ	-76 dBm
μ_{B_j,N_j}	25%

$$\omega(d) = P_{tx}(\frac{\lambda_c}{4\pi d})^2 \tag{9}$$

Since in CSMA/CA a given station STA_i senses the channel by measuring the received power $P_{r,i}$. If $P_{r,i} < \epsilon$ then the physical layer informs the MAC that the channel is idle, otherwise, STA_i enters in contention mode, or "frozen" the value of its current backoff timer. A terminal STA_i is said to be hidden from the terminal STA_j (and vice-versa) if and only if the power received by STA_i issued by the station STA_j, denoted by $P_{i,j}$ satisfies the following inequality

$$P_{i,j} = P_{tx}(\frac{\lambda_c}{4\pi d_{i,j}})^2 < \epsilon, \tag{10}$$

where $d_{i,j}$ is the distance between STA_i and STA_j. Once more in modelling the hidden terminal we considered the free-space propagation law, however, our implementation is generic and can include other fading such as shadowing, multipath propagation. It is obvious to see that the capture (near-far problem) as well as the hidden terminal depends on location of the user.

We used the above techniques and parameter for collecting statistics used for estimating the performance of our algorithm in terms of power, however it is obvious to mention that a gain in throughput and delay is improved by load sharing. In our experiments, we used a uniform distribution to place STA in the BSA. For each STA in each BSA we collected statistics by observing 100 packets. The value p_h (probability of hidden terminal) was obtained by taking the maximum number of hidden for a given set of stations in BSA normalized to the total number of STA. Thus from tab.2, one see that, in some cases, load sharing makes the problem of hidden terminal even worse. This is because when the STA asks for reassociation (from A to B or from A to C) doesn't have any possibility to estimate the location of other STA associated with B or C. The same thing applied to the B and C, they can't have any idea if the reassociated station makes the hidden terminal worst or not. The simulation results are summarized in tab.2, where any parameter with subscript LS means its value after load-sharing algorithm, e.g μ_r^{LS} is the value of μ_r after load sharing. Fig.3 shows a snapshot of the simulation results after load-sharing. Tab.2 shows that Power saving in the excess power is from 10 to 50% (see the value of $\frac{\eta_i}{\eta_i^{LS}}$), this impacted on total

Table 2: Simulation results

AP	N_i	N_i^{LS}	p_h	p_h^{LS}	$\frac{\mu_r}{\mu_r^{LS}}$	$\frac{P_t}{P_t^{LS}}$	$\frac{\eta_i}{\eta_i^{LS}}$
A	32	19	0.78	0.73	0.43	1.0724	0.43
B	2	3	0.5	0.0667	0/0	1	0/0
C	2	12	0.5	0.333	0.033	0.7769	0.033
A	24	19	0.83	0.6316	1.1875	1.0455	1.1875
B	2	3	0.5	0.333	0.33	0.9623	0.33
C	2	5	0	0.4	0/0.1	0.9091	0/0.1
A	16	11	0.5	0.54	2	1.1525	0.54
B	2	3	0.5	0.67	0.25	0.9940	0.25
C	2	3	0.5	0.67	0/0.02	0.9980	0/0.02
A	10	10	0.5	0.5	1	1	1
B	2	2	0.5	0.5	0/0	1	0/0
C	2	2	0.5	0.5	0/0	1	0/0

power saving of $P_t = M \times P_{min}(1 + \gamma\mu_r)$ ranging from 5-15%. While the access point, experiencing high-load, get benefit from the load-sharing, however power, in the access point B and C, is degraded, e.g. when $N_j = 32$, the system power in BSA (average) increased by $\approx 23\%$, this "worst" scenario occurred because p_h^{LS} increased comparing to p_h.

5. CONCLUSION

In this paper a load sharing algorithm for energy efficient protocol compliant with 802.11 was presented. The core of the algorithm is based on the estimation of the average collision per packet for each user. This parameter is used as a basis for reassociation to a "near-by" access point experiencing low number of associated terminal. We proved that under the condition that the mobile station in a given basic services area are i.i.d then the instantaneous value of the collision per user per packet is Gaussian distributed random variable with mean equal to the average number of collision/user/packet. The experimental results showed that the load-sharing reduces the excess power (in the highly loaded BSS) by 50%, thus the average system power (P_t) from $5 - 15\%$. However load-sharing algorithm, in some cases, has negative impact in neighbouring access point, since the reassociation process doesn't take into account the probability of hidden terminal at the neighbouring access point. Thus, further improvements for this algorithm will be carried out in our future research.

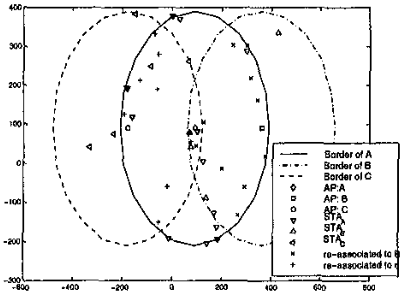

Figure 3: After Load-sharing algorithm

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