ΕΘΝΙΚΟ ΜΕΤΣΟΒΙΟ ΠΟΛΥΤΕΧΝΕΙΟ
ΣΧΟΛΗ ΗΛΕΚΤΡΟΛΟΓΩΝ ΜΗΧΑΝΙΚΩΝ
ΚΑΙ ΜΗΧΑΝΙΚΩΝ ΥΠΟΛΟΓΙΣΤΩΝ

TECHNISCHE UNIVERSITÄT DRESDEN

ΤΟΜΕΑΣ ΕΠΙΚΟΙΝΩΝΙΩΝ ΗΛΕΚΤΡΟΝΙΚΗΣ ΚΑΙ ΣΥΣΤΗΜΑΤΩΝ ΠΛΗΡΟΦΟΡΙΚΗΣ

Μελέτη Επίδοσης Συστήματος PLC HomePlug Command and Control υπό Ρεαλιστικές Συνθήκες Κίνησης σε Ευφυές Δίκτυο.

ΔΙΠΛΩΜΑΤΙΚΗ ΕΡΓΑΣΙΑ

Ιωάννα Π. Καγιαννά
Ioanna P. Kagianna

Επιβλέπων : Νικόλαος Μήτρου
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Αθήνα, Δεκέμβριος 2013

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Αθήνα, Δεκέμβριος 2013

....
Νικόλαος Μήτρου   Μιχαήλ Θεολόγου   Συμεών Παπαβασιλείου.
Καθηγητής Ε.Μ.Π.   Καθηγητής Ε.Μ.Π.   Αναπληρωτής Καθηγητής
                                                                          Ε.Μ.Π

....

Ιωάνα Π. Καγιαννά

Διπλωματούχος Ηλεκτρολόγος Μηχανικός και Μηχανικός Υπολογιστών Ε.Μ.Π.

Performance Study of HomePlug Command and Control PLC System
under Realistic Smart Grid Traffic Conditions

Abstract

Nowadays, the human society has a lot of needs and demands that constantly increase and technology is called to fulfill them. In the area of electricity supply, increasing load, security and convenience demands by consumers and markets have led to the evolution of the electricity grid to the contemporary Smart Grid. Intelligence, efficiency, security and reliability are some of the prominent characteristics that enable Smart Grid to play a determinant role in our era.

This study aims to present a possible Smart Grid system and study its performance. First of all, ten Smart Grid applications that could possibly coexist in a future Smart Grid are described and then some mathematical models for the traffic that each application may produce are derived, based on data provided by the relevant literature. Afterwards, these models are combined to form a realistic complex model for the traffic produced in the system when all the applications are taken into account. Finally, the performance of the system is studied and analyzed in terms of aggregate throughput for six different scenarios of working applications. The results presented in this work are derived by the use of a combination of analytical mathematical models and Matlab simulations.

Μελέτη Επίδοσης Συστήματος PLC HomePlug Command and Control υπό Ρεαλιστικές Συνθήκες Κίνησης σε Ευφυές Δίκτυο

Περίληψη

Στη σύγχρονη εποχή, η ανθρώπινη κοινωνία έχει πλειάδα αναγκών που συνεχώς αυξάνουν και η τεχνολογία καλείται να τις εκπληρώσει. Στον τομέα της παροχής ηλεκτρικής ενέργειας, η αυξανόμενη ζήτηση σε ηλεκτρικό φορτίο και οι απαιτήσεις για ασφάλεια και διευκόλυνση στις διάφορες υπηρεσίες από τους καταναλωτές και τις αγορές οδήγησαν στην εξέλιξη του παραδοσιακού Ηλεκτρικού Δικτύου στο σύγχρονό του Έξυπνο Δίκτυο (Smart Grid). Ευφυΐα, αποδοτικότητα, ασφάλεια και αξιοπιστία είναι μερικά από τα εξέχοντα χαρακτηριστικά του Έξυπνου Δικτύου που το κάνουν να παίζει καθοριστικό ρόλο στην εποχή μας.

Αυτή η μελέτη στοχεύει στο να παρουσιάσει ένα πιθανό Έξυπνο Δίκτυο και να μελετήσει την επίδοσή του. Αρχικά, δέκα εφαρμογές που θα μπορούσαν να συνυπάρξουν σε ένα μελλοντικό Έξυπνο Δίκτυο περιγράφονται και στη συνέχεια προτείνονται μαθηματικά μοντέλα που περιγράφουν την κίνηση που κάθε μία από τις εφαρμογές αυτές προκαλεί στο σύστημα όταν λειτουργεί, με βάση δεδομένα που προέρχονται από σχετική βιβλιογραφία. Αυτά τα μοντέλα συνδυάζονται έπειτα για τη δημιουργία ενός σύνθετου μαθηματικού μοντέλου που θα περιγράφει την κίνηση του δικτύου όταν και οι δέκα εφαρμογές θα συλλειτουργούν στο δίκτυο. Τέλος, μελετάται και αναλύεται η επίδοση του συστήματος σε όρους συνολικής απόδοσης για έξι διαφορετικά σενάρια βάσει των εφαρμογών που λειτουργούν στο σύστημα. Τα αποτελέσματα που παρουσιάζονται σε αυτή την εργασία προέρχονται από συνδυασμό χρήσης αναλυτικών μαθηματικών μοντέλων και του προγραμματιστικού εργαλείου, Matlab.

Λέξεις Κλειδιά: **Ευφυές Δίκτυο, Εφαρμογές Ευφυούς Δικτύου, μαθηματικά μοντέλα, απόδοση, πραγματικές συνθήκες κίνησης, Matlab**

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More specifically, I have to express my deepest thanks and gratitude to prof. Nikolaos Mitrou who was always willing to help or guide me.

This Diploma Thesis was carried out in the TU-Dresden, which I attended as an Erasmus Student during the summer semester of 2013. For this reason I would like to thank the Chair for Telecommunications in the TU-Dresden and especially Prof. Dr.-Ing. Lehnert for the great opportunity that he gave me by accepting me as an Erasmus Student in his team. Moreover I would like to thank my supervisor M.Sc. Stanislav Mudriievskyi, for without our cooperation and his constant help and support, this study would have been impossible.

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Εκτενής Περίληψη Διπλωματικής εργασίας με τίτλο:

Μελέτη Επίδοσης Συστήματος PLC HomePlug Command and Control υπό Ρεαλιστικές Συνθήκες Κίνησης σε Ευφυές Δίκτυο.

Πρόλογος

Η ανάπτυξη του Ηλεκτρικού Δικτύου ξεκίνησε πριν από έναν αιώνα περίπου στις πιο βιομηχανικά ανεπτυγμένες χώρες. Στη σημερινή εποχή, η ανθρώπινη κοινωνία έχει πολλές και ολοένα αυξανόμενες ανάγκες και απαιτήσεις τις οποίες η τεχνολογία καλείται να τις εκπληρώσει. Στον τομέα της ηλεκτρικής ενέργειας, οι απαιτήσεις για ολοένα αυξανόμενο ηλεκτρικό φορτίο, ασφάλεια και ανέσεις από τους καταναλωτές αλλά και από τις αγορές έχουν οδηγήσει στην εξέλιξη του Ηλεκτρικού Δικτύου στο σύγχρονο του Ευφυές Δίκτυο. Ευφυΐα, αποδοτικότητα, ασφάλεια και αξιοπιστία είναι μερικά από τα εξέχοντα χαρακτηριστικά του Ευφυούς Δικτύου , που του επιτρέπουν να παίζει ένα καθοριστικό ρόλο στη σύγχρονη εποχή. Η χρήση της πληροφορικής, των συστημάτων επικοινωνίας και των ηλεκτρονικών ισχύος έχουν μεταμορφώσει τη μετάδοση και διανομή της ηλεκτρικής ενέργειας.

Η τεχνολογία Power Line Communications (PLC) αποτελεί μια ελκυστική εναλλακτική για τη μετάδοση πληροφοριών και προσφέρει οικονομικά βιώσιμες λύσεις για επικοινωνίες. Για να επιτευχθεί η ευρύτερη χρήση αυτής της τεχνολογίας είναι απαραίτητη η ανάπτυξη πρωτοκόλλων κοινά αποδεκτών. Γι' αυτό, το πρωτόκολλο HomePlug Command and Control Specification (HomePlug C&C) ορίστηκε από την HomePlug Powerline Alliance *'με σκοπό την ικανοποίηση απαιτήσεων για ένα εύρωστο και ανθεκτικό από διάφορους τύπους παρεμβολών σύστημα'*.

Εφαρμογές Ευφυούς Δικτύου

Δέκα πιθανές εφαρμογές που μπορεί να συλλειτουργούν σε ένα Ευφυές Ηλεκτρικό Δίκτυο είναι οι εξής:

I. **SCADA,** που αντιστοιχεί σε Επίβλεψη Ελέγχου και Απόκτησης Δεδομένων (Supervisory Control and Data Acquisition) και αναφέρεται σε συστήματα/ εφαρμογές που χρησιμοποιούνται για παρακολούθηση του ηλεκτρικού δικτύου και έλεγχο των αυτόματων συσκευών.

II. **Λήψη και αναβάθμιση νέου λογισμικού (Software download/upgrade firmware)**

III. **Έλεγχος του φωτεινών Σηματοδοτών και Κυκλοφοριακής Κίνησης (Street Lighting and Traffic Control).** Αυτού του είδους τα συστήματα είναι συστήματα τηλεδιαχείρισης που επιτρέπουν την αυτόματη αντίδραση του συστήματος φωτεινών σηματοδοτών σε εξωτερικές παραμέτρους, όπως καιρικές συνθήκες, παραμένον επίπεδο φυσικού φωτισμού ημέρας, ατυχήματα ή πυκνότητα της κυκλοφορίας.

IV. **Αυτοματισμός Διανομής Ενέργειας (Distribution automation (DAS)).** Πρόκειται για συστήματα υπεύθυνα για τον αυτοματισμό της μεταγωγής, της λειτουργίας και του έλεγχο του δικτύου διανομής από μακριά.

V. **Διαχείριση Φορτίου (Load Management)** είναι μια έξυπνη εφαρμογή του Ευφυούς Δικτύου υπεύθυνη για την εξισορρόπηση της προσφοράς ηλεκτρικής ενέργειας στο δίκτυο με το ηλεκτρικό φορτίο, προκειμένου να βελτιστοποιηθεί το

κόστος παραγωγής της ενέργειας, ανάλογα με τη συμπεριφορά των διαφορετικών τύπων πελατών, να ενισχύει την αξιοποίηση της ενέργειας ή την αξιοπιστία του συστήματος.

VI. **Εφαρμογή Συναγερμού (Alarm Management)** είναι μια εφαρμογή που ανιχνεύει ένα γεγονός που απαιτεί την προσοχή ολόκληρου του συστήματος ελέγχου και μεταδίδει αυτή την πληροφορία συναγερμού σε όλο το σύστημα, προκειμένου να αποφευχθούν τυχόν ανεπιθύμητες καταστάσεις.

VII. **Επίβλεψη Δικτύου με χρήση Video (Video Surveillance)** για λόγους ασφάλειας.

VIII. **Τηλεφωνία (Operational Telephony)** που παρέχει άμεση αμφίδρομη σύνδεση ήχου με το Κέντρο Λειτουργίας Δικτύου.

IX. **Ευφυείς Μετρητές (Smart meters).** Πρόκειται για προηγμένους μετρητές ενέργειας που προσδιορίζουν την κατανάλωση ενέργειας του καταναλωτή με περισσότερες λεπτομέρειες από ό,τι ένας συμβατικός μετρητής και με ασφάλεια μεταδίδει τις πληροφορίες αυτές στην εταιρεία κοινής ωφελείας από δύο συστήματα επικοινωνιών.

X. **On demand meter reading** για παρακολούθηση σε πραγματικό χρόνο τιμών διαφόρων μεγεθών ή την παρουσία του ρεύματος ή άλλες παραμέτρους.

Έκφραση του χρόνου μεταξύ 2 διαδοχικών αφίξεων πακέτων στο σύστημα (Interarrival Time(T)) συναρτήσει του μεγέθους του πακέτου (L) και του Εύρους Ζώνης (B)

Για τη μελέτη της επίδοσης ενός καναλιού Smart Grid όταν οι προαναφερθέντες εφαρμογές λειτουργούν, ο υπολογισμός των interarrival times των πακέτων τους σε όρους μεγέθους πακέτου και εύρους ζώνης είναι απαραίτητος. Υποθέτοντας ότι τα πακέτα εισέρχονται στο σύστημα για ένα συγκεκριμένο χρονικό διάστημα, για παράδειγμα για 24 ώρες, όπως φαίνεται στην παρακάτω εικόνα:
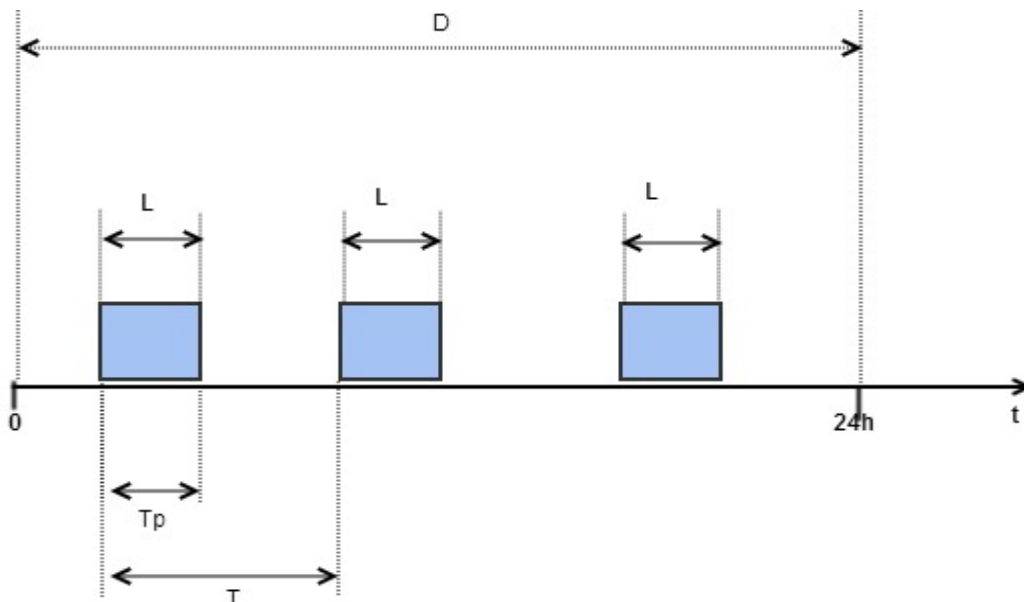
Εικόνα 2.5: *Αφίξεις πακέτων στο σύστημα σε διάστημα 24 ωρών*

Αποδείχθηκε ότι ο χρόνος μεταξύ 2 διαδοχικών αφίξεων πακέτων στο σύστημα - **Interarrival Time(T) -** ισούται με τον εξής λόγο: $T = \frac{L}{B}$ (1).

Υπολογισμός του 'Interarrival Time' κάθε εφαρμογής ευφυούς δικτύου

Στον παρακάτω πίνακα περιέχονται οι τιμές του 'datarate' και του μεγέθους των πακέτων για κάθε εφαρμογή (τα δεδομένα αυτά συλλέχθηκαν μετά από βιβλιογραφική έρευνα):

Πίνακας 2.1: *Πίνακας 'datarate' και μεγέθους πακέτου των εφαρμογών ευφυούς δικτύου*

#	Εφαρμογές Ευφυούς Δικτύου	Datarate(kbps)	Μέγεθος Πακέτου
1	SCADA	[1.8,9.6]	512 bits
2	Software download/upgrade firmware		
	upstream	32	[10kbytes,100kbytes]
	downstream	32	[100kbytes,10Gbytes]
3	Street lighting and traffic control	0.025	512 bits
4	Distribution automation and traffic protection	18	150-500 bytes
5	Load Management	50	512 bits
6	Alarm Management	9.6	512 bits
7	Video Surveillance	[15,128]	512 bits
8	Operational telephony	8	512 bits
9	Smart Meters		
	upstream	5.3	[2000, 10000] bytes
	downstream	5.3	[50, 400] bytes
10	On demand-reading		
	upstream	100	[100, 500]
	downstream	100	[50,100]

Παρατηρώντας τον Πίνακα 2.1, είναι προφανές ότι για ορισμένες εφαρμογές οι τιμές είτε του ρυθμού δεδομένων (data rate) είτε του μεγέθους πακέτου ποικίλουν σε ένα διάστημα, ενώ για άλλες εφαρμογές, αυτές οι τιμές του, που βρέθηκαν στη βιβλιογραφία, είναι συγκεκριμένες. Αυτό εξαρτάται από την ποσότητα των δεδομένων που βρέθηκαν στη σχετική βιβλιογραφία.

Υπολογισμός μαθηματικών μοντέλων για την περιγραφή της κίνησης που παράγεται από καθεμία από τις προαναφερθέντες εφαρμογές ευφυούς δικτύου

Η κίνηση που παράγεται από κάθε εφαρμογή θα περιγραφεί ως μια συνάρτηση κατανομής με τυχαία μεταβλητή το Interarrival Time της κάθε εφαρμογής .

Όσον αφορά τις εφαρμογές στον Πίνακα 2 , θα μπορούσε να υποτεθεί ότι μια κανονική κατανομή (normal distribution) με τυχαία μεταβλητή το Interarrival Time κάθε μίας από αυτές τις εφαρμογές θα μπορούσε περιγράφει την κίνηση που αυτή παράγει. Η υπόθεση αυτή βασίζεται κυρίως στις περιγραφές αυτών των εφαρμογών και τα δεδομένα που βρέθηκαν σε σχετική βιβλιογραφία.

Πίνακας 2.3: *Μέση τιμή και τυπική απόκλιση του 'interarrival time' για τις εφαρμογές που ακολουθούν 'normal' κατανομή*

	Εφαρμογές Ευφυούς Δικτύου	**Μέση τιμή(sec)**	**Τυπική απόκλιση(sec)**
1	SCADA	0.1689	0.1156
2	Software download/upgrade firmware		
	upstream	13.75	11.25
	downstream	1262.5	1237.5
4	Distribution automation and traffic protection	0.1444	0.0778
7	Video Surveillance	0.019	0.015
9	Smart Meters		
	upstream	1.132	0.0001
	downstream	0.0424	0.0001
10	On demand-reading		
	upstream	0.024	0.016
	downstream	0.006	0.002

Σύμφωνα με το [39], μια τυχαία μεταβλητή Χ είναι μια κανονική τυχαία μεταβλητή (ή το Χ είναι κανονικά διανεμηθεί) με παραμέτρους μ και $\sqrt{\sigma}$ αν έχει συνάρτηση πυκνότητας

$$:f(x) = \frac{1}{\sigma \cdot \sqrt{2\pi}} \cdot \exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right) \text{ for } -\infty \leq x \leq \infty \ (2)$$

Αυτή η πυκνότητα είναι μια καμπύλη σε σχήμα καμπάνας που είναι συμμετρικός γύρω από μ:
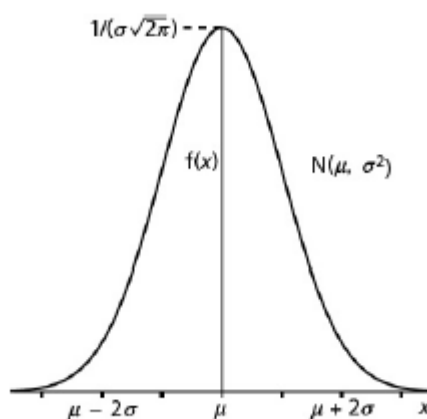
Εικόνα 2.6: *Normal density function*

Όσον αφορά τις υπόλοιπες εφαρμογές στον Πίνακα 1, για τις οποίες δίνεται μία εκτιμούμενη τιμή των αντίστοιχων Interarrival Times, θα μπορούσε να υποτεθεί ότι μια εκθετική κατανομή με ρυθμό λ μπορεί να περιγράψει την κίνηση που κάθε μία από αυτές παράγουν, δεδομένου ότι δεν υπάρχουν αρκετά στοιχεία στη βιβλιογραφία , ώστε να είναι δυνατόν να προσδιοριστεί μια ακριβής κατανομή του Interarrival Time και να υπολογιστούν παράμετροι των άλλων πιθανών κατανομών (π.χ. κανονική κατανομή).
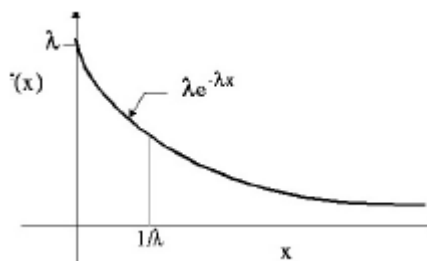
#	Εφαρμογές Ευφυούς Δικτύου	Interarrival time (sec)
3	Street lighting and traffic control	20.5
5	Load Management	0.00102
6	Alarm Management	0.05333
8	Operational telephony	0.064

Μια συνεχής τυχαία μεταβλητή Χ θεωρείται ότι ακολουθεί εκθετική κατανομή με παράμετρο λ, λ> 0, αν έχει συνάρτηση πυκνότητας:

$$f(x) = \lambda \cdot \exp(\lambda \cdot x), \text{ for x} \geq 0 \ (3)$$

και απεικονίζεται:

Εικόνα 2.16: *Exponential density function*

Τελικό Μοντέλο Κίνησης

Αναλυτική Έκφραση

Για να βρεθεί μια αναλυτική έκφραση για το τελικό μοντέλο που θα περιγράφει την παραγόμενη από όλες τις εφαρμογές κίνηση, όλες οι κατανομές των εφαρμογών προσεγγίζονται με Poisson κατανομές.
Γενικά [36] :

Έστω Ν1 (t) , ... , Νk (t) κατανομές Poisson με παραμέτρους λ1 , ... , λk . Τότε, η υπέρθεση αυτών των διαδικασιών Poisson είναι μια νέα διαδικασία Poisson με ρυθμό : $\lambda = \sum_{i=1}^{k} \lambda_i$ (4)

Στην περίπτωσή που εξετάζεται, το τελικό μοντέλο κίνησης, το οποίο προκύπτει ως υπέρθεση των διαδικασιών Poisson που περιγράφουν την κίνηση της κάθε εφαρμογής είναι μια διαδικασία Poisson με παράμετρο λ : $\lambda = \sum_{i=1}^{13} \lambda_i = 430$ (5), όπου λi είναι μια παράμετρος Poisson από τον πίνακα 4 .

#	Εφαρμογές Ευφυούς Δικτύου	λ της κατανομής Poisson
1	SCADA	5.92105
2	Software download/upgrade firmware	
	upstream	0.07272
	downstream	0.00079
3	Street lighting and traffic control	0.0488
4	Distribution automation and traffic protection	6.923]
5	Load Management	97.1
6	Alarm Management	18.75
7	Video Surveillance	52.447
8	Operational telephony	15.6
9	Smart Meters	
	upstream	0.88333
	downstream	23.555
10	On demand-reading	
	upstream	41.7
	downstream	166.67

Έτσι , το αναλυτικό τελικό μοντέλο που περιγράφει τη συνολική κυκλοφορία είναι: $Poisson = \dfrac{e^{-430} \cdot \lambda 430^{x}}{x!}$ (6).

Γενικά, μια κατανομή Poisson είναι μία διακριτή κατανομή πιθανότητας που εκφράζει την πιθανότητα ενός δεδομένου αριθμού γεγονότων που συμβαίνουν σε ένα σταθερό χρονικό διάστημα ή/και χώρο, αν αυτά τα γεγονότα συμβαίνουν με ένα γνωστό μέσο ρυθμό και ανεξάρτητα από τη χρονική στιγμή του που συνέβη το προηγούμενο συμβάν [3] . Έτσι, η Σχέση 6 παρέχει την πιθανότητα ενός δεδομένου αριθμού αφίξεων πακέτων που συμβαίνουν σε ένα χρονικό διάστημα ($-\infty < t < \infty$) . Σύμφωνα με την Σχέση 6 και [36] η αναμενόμενη τιμή του Interarrival Time στο τελικό μοντέλο όταν όλες οι εφαρμογές στέλνουν πακέτα είναι : E[T] = 1/430 = 0.002325sec.

Μοντέλο της συνολικής κίνησης με χρήση Matlab

Ως επαλήθευση των αποτελεσμάτων που βρέθηκαν με χρήση του μαθηματικό μοντέλου κίνησης που αναπτύχθηκε στην προηγούμενη ενότητα, η εκτιμώμενη τιμή των interarrival times όταν όλες οι εφαρμογές συλλειτουργούν υπολογίστηκε και με εξομοίωση του συστήματος σε Matlab.
Η αναμενόμενη τιμή του Interarrival Time στο τελικό μοντέλο με Matlab υπολογίζεται:
E [T] = 0.0031sec.

Είναι αξιοσημείωτο ότι η αναμενόμενη τιμή του Interarrival Time όπως υπολογίζεται από το αναλυτικό μοντέλο και αυτή που υπολογίζεται με τη βοήθεια του Matlab είναι της ίδιας τάξης μεγέθους. Το γεγονός αυτό υποδεικνύει ότι η αναλυτική προσέγγιση είναι αρκετά καλή, δεδομένου ότι τα αποτελέσματα που παράγει επαληθεύονται από το κώδικά σε Matlab, ο οποίος είναι ακριβής.

Υπολογισμός Επίδοσης

Στην Έδρα των Τηλεπικοινωνιών του Τεχνικού Πανεπιστημίου της Δρέσδης (Technical University of Dresden) έχει ήδη αναπτυχθεί ένα αναλυτικό μοντέλο για το επίπεδο MAC ενός συστήματος Narrowband Power Line Communications (NB-PLC system), που προορίζεται να χρησιμοποιηθεί για εφαρμογές που αφορούν το Έξυπνο Δίκτυο (Smart Grid Applications).

Σύμφωνα με το [37], η επίδοση από σημείο σε σημείο του δικτύου επικοινωνιών στο επίπεδο MAC μπορεί να περιγραφεί ως εξής:

$$S = \frac{\overline{U}}{\overline{B}} \qquad (7)$$

where:

$\overline{U} = T_p \cdot P_s$ the average transmission time within one frame   (8)

$\overline{B} = \tau + I + \overline{Y} + T_p$ the average frame duration   (9)

T_p: χρόνος μετάδοσης ενός πακέτου στο σύστημα

P_s: πιθανότητα επιτυχούς μετάδοσης

τ: καθυστέρηση διάδοσης

I: constant frame overhead

$\overline{Y}$: the average winner backoff time

Από τη μελέτη της επίδοσης του συστήματος όπως περιγράφεται στο [37] προκύπτει η Σχέση 4.4 που υπολογίζει την επίδοση του συστήματος υπό **greedy traffic conditions:**

$$S = \frac{T_p \cdot \left(1 - \left(\sum_{i-1}^{CW-i} \left(\frac{1}{CW^N} \cdot \sum_{j=2}^{N} \left(\binom{N}{j} \cdot (CW-j)^{N-j} \right) + \frac{1}{CW^N} \right) \right) \right)}{\tau + I + \sum_{i=1}^{CW} y_i \cdot \left[(1 - \frac{y_i - 1}{CW})^N - (1 - \frac{y_i}{CW})^N \right] + T_p} \qquad (10)$$

Σε ένα τέτοιο σύστημα, κάθε πηγή έχει συνέχεια πληροφορίες προς μετάδοση και ποτέ δε βρίσκεται σε αδράνεια. Δεν υπάρχει ποτέ συμφόρηση στη πλευρά του αποστολέα των πληροφοριών, αφού ένα νέο πακέτο παράγεται μόνο μετά την ολοκλήρωση της μετάδοσης του προηγούμενου πακέτου. Η επίδοση ενός συστήματος υπό τέτοιες συνθήκες είναι η μέγιστη δυνατή για το σύστημα [38].

Όμως απαιτείται πιο ενδελεχής μελέτη της επίδοσης του συστήματος υπό ρεαλιστικές συνθήκες. Δηλαδή, στην περίπτωση αυτή δεν είναι σίγουρο ότι κάθε πηγή έχει συνέχεια ένα πακέτο προς μετάδοση. Οπότε, υπό ρεαλιστικές συνθήκες κίνησης, υπάρχει ένα χρονικό διάστημα μεταξύ των αφίξεων στο σύστημα δύο διαδοχικών πακέτων πληροφορίας. Αυτό το χρονικών διάστημα μεταξύ των δύο διαδοχικών αφίξεων στο σύστημα πρέπει να συμπεριληφθεί στον υπολογισμό της επίδοσης του συστήματος.

Η επίδοση του συστήματος περιγράφεται και πάλι από την Σχέση 7. Η διαφορά της επίδοσης του συστήματος υπό ρεαλιστικές συνθήκες, σε σχέση με την αντίστοιχη επίδοση σε σύστημα με συνθήκες **greedy traffic,** βρίσκεται στον παρανομαστή της Σχέσης 9. Η

μεταβλητή I στην Σχέση 9 εκφράζει το μέγεθος της επικεφαλίδας πακέτου - **constant frame overhead** - που περιλαμβάνει τα κομμάτια του εκπεμπόμενου πακέτου που είναι σταθερά και δεν αλλάζουν για δοθέν σύστημα, όπως τα guard intervals και το acknowledgement. Η μεταβλητή I στη Σχέση 4.4 αντικαθιστάται από τη μεταβλητή I΄, που περιλαμβάνει και την αναμενόμενη τιμή του χρονικού διαστήματος μεταξύ των αφίξεων δύο διαδοχικών πακέτων.

Δηλαδή είναι: $I΄ = I + E[T]$ (11)

Όπως φαίνεται στην Εικόνα 2.5, το χρονικό διάστημα μεταξύ των αφίξεων δύο διαδοχικών πακέτων περιλαμβάνει και το χρόνο μετάδοσης του πρώτου. Έτσι, ο όρος Tp πρέπει να αφαιρεθεί από τον παρανομαστή, αφού περιλαμβάνεται στον όρο E[T].

Επομένως, η επίδοση του συστήματος τώρα μπορεί να γραφεί ως εξής:

$$S = \frac{T_p \cdot \left(1 - \left(\sum_{i-1}^{CW-i} \left(\frac{1}{CW^N} \cdot \sum_{j=2}^{N} \left(\binom{N}{j} \cdot (CW-j)^{N-j} \right) + \frac{1}{CW^N} \right) \right) \right)}{\tau + I + E[T] + \sum_{i=1}^{CW} y_i \cdot \left[(1 - \frac{y_i - 1}{CW})^N - (1 - \frac{y_i}{CW})^N \right]}$$ (12)

Η Σχέση 12 αναφέρεται στη συνολική επίδοση του συστήματος στην περίπτωση που πάνω από μία εφαρμογές συλλειτουργούν. Ο όρος $E[T]$ είναι η μέση αναμενόμενη τιμή του χρονικού διαστήματος μεταξύ των αφίξεων δύο διαδοχικών πακέτων και εξαρτάται από το χρονικό διάστημα μεταξύ των αφίξεων δύο διαδοχικών πακέτων κάθε εφαρμογής ξεχωριστά. Εν γένει, το χρονικό διάστημα μεταξύ των αφίξεων δύο διαδοχικών πακέτων που εισέρχονται σε ένα σύστημα δεν είναι σταθερό και ίδιο για όλα τα πακέτα.

Αποτελέσματα

A. *Επίδοση του συστήματος υπό ρεαλιστικές συνθήκες*

Μελετάται η επίδοση του συστήματος υπό ρεαλιστικές συνθήκες σε όρους συνολικής απόδοσης , μεταβάλλοντας τις διάφορες παραμέτρους της κίνησης του μοντέλου του συστήματος.

- τ = 6.667 * 10^−9 sec, I = 1.827 * 10^−2 sec, B = 56 kbps (όπως στο *Mudriievskyi et al*).

- Κάθε εφαρμογή έχει διαφορετικό μέγεθος πακέτων από τις υπόλοιπες.

- Τp είναι ο χρόνος μετάδοσης και εξαρτάται από το μέγεθος του πακέτου

Μελετούνται πέντε διαφορετικά σενάρια από εφαρμογές που συνυπάρχουν κάθε φορά στο σύστημα. Για κάθε σενάριο υπολογίζεται η μέση αναμενόμενη τιμή του χρονικού διαστήματος μεταξύ των αφίξεων δύο διαδοχικών πακέτων και παρουσιάζεται για κάθε περίπτωση ένα διάγραμμα της απόδοσης του συστήματος ως προς το contention window (CW) για διαφορετικό αριθμό κόμβων (εξαρτάται από το σενάριο) και βρίσκεται η βέλτιστη τιμή για το contention window (CW) σε κάθε περίπτωση.

Για παράδειγμα, στο σενάριο σύμφωνα με το οποίο συλλειτουργούν στο σύστημα οι εφαρμογές SCADA και Smart metering και η μέση αναμενόμενη τιμή του χρονικού διαστήματος μεταξύ των αφίξεων δύο διαδοχικών πακέτων υπολογίζεται με τη βοήθεια του Matlab: E[T] = 0.1676 sec.

Στην Εικόνα 5.1 έχει σχεδιαστεί η επίδοση του συστήματος versus contention window:
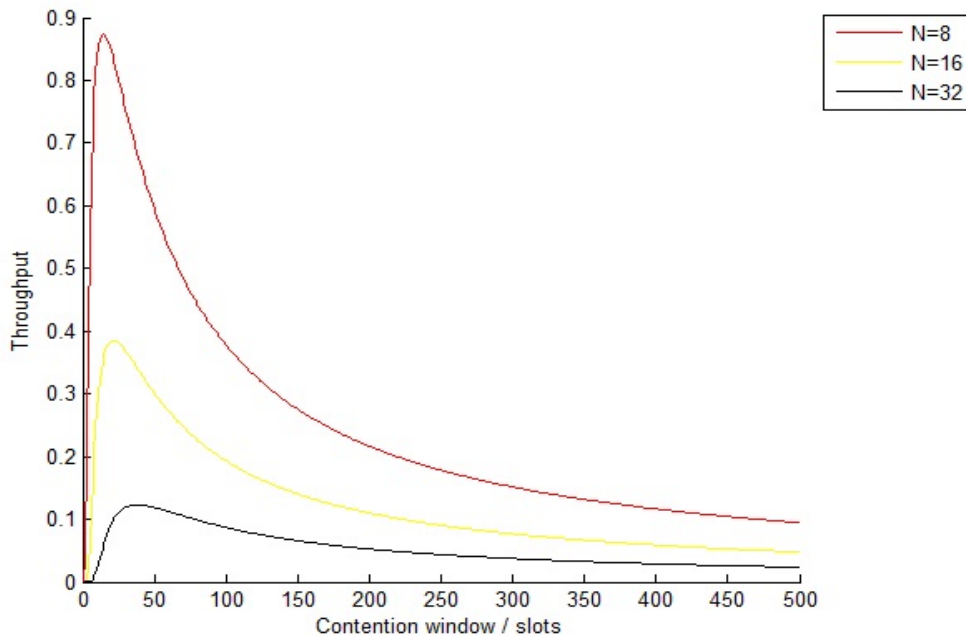
Εικόνα 5.1: Επίδοση vs *contention window/slots για το σενάριο 1 για διαφορετικό αριθμό κόμβων*

Η βέλτιστη τιμή για το contention window (CW) για διαφορετικό αριθμό κόμβων φαίνεται στον πίνακα 5.1:

Πίνακας 5.1*: Η βέλτιστη τιμή Contention Window για διαφορετικό αριθμό κόμβων για το σενάριο 1*

Number of nodes (N)	Throughput	Optimal Contention Window
8	0.9146	19
16	0.5195	25
32	0.1432	41

B. *Επίδοση του συστήματος υπό ρεαλιστικές συνθήκες για διαφορετικό κανάλι*

- Το εύρος ζώνης του καναλιού δεν είναι πλέον 56 kbps αλλά θεωρείται 400 kbps έτσι ώστε όλες οι προαναφερθέντες εφαρμογές να μπορούν να συλλειτουργούν στο σύστημα,

- $\tau = 6.667 * 10^{-9}$ sec, I $= 1.827 * 10^{-2}$ sec.

Τώρα θεωρούνται τρία διαφορετικά σενάρια συλλειτουργούντων εφαρμογών και για κάθε σενάριο υπολογίζεται η μέση αναμενόμενη τιμή του χρονικού διαστήματος μεταξύ των αφίξεων δύο διαδοχικών πακέτων και παρουσιάζεται για κάθε περίπτωση ένα διάγραμμα της απόδοσης του συστήματος ως προς το contention window (CW) για διαφορετικό αριθμό κόμβων (εξαρτάται από το σενάριο) και βρίσκεται η βέλτιστη τιμή για το contention window (CW) σε κάθε περίπτωση.

Για παράδειγμα, στο σενάριο σύμφωνα με το οποίο οι εφαρμογές **Load Management, Alarm Management** και **Distribution Automation** συλλειτουργούν, η εκτιμώμενη μέση

τιμή του Interarrival time έχει υπολογιστεί μέσω προσομοίωσης με Matlab να είναι: E[T] = 0.1760sec.

Στην Εικόνα 5.1 έχει σχεδιαστεί η επίδοση του συστήματος versus contention window για διαφορετικό αριθμό κόμβων και για κανάλι με εύρος ζώνης 400kbps:
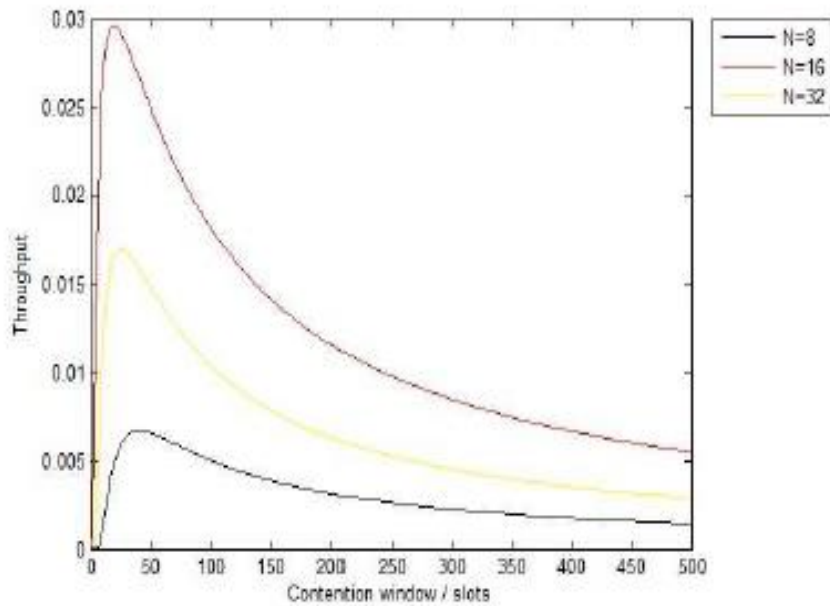
Εικόνα 5.7: Επίδοση vs *contention window/slots για το σενάριο 2για διαφορετικό αριθμό κόμβων*

Η επίδοση του συστήματος μπορεί να βελτιωθεί αν το κανάλι που χρησιμοποιείται δεν έχει τόσο πολύ περισσότερο εύρος ζώνης από όσο απαιτείται από τις εφαρμογές. Προσθέτοντας τα εύρη ζώνης που απαιτεί η κάθε εφαρμογή ξεχωριστά, προκύπτει ότι ένα κανάλι εύρους ζώνης 80kbps θα ήταν κατάλληλο για να συλλειτουργούν οι προαναφερθέντες εφαρμογές. Στην εικόνα 5.8, η επίδοση του συστήματος vs του contention window σχεδιάστηκε για διαφορετικό αριθμό κόμβων:
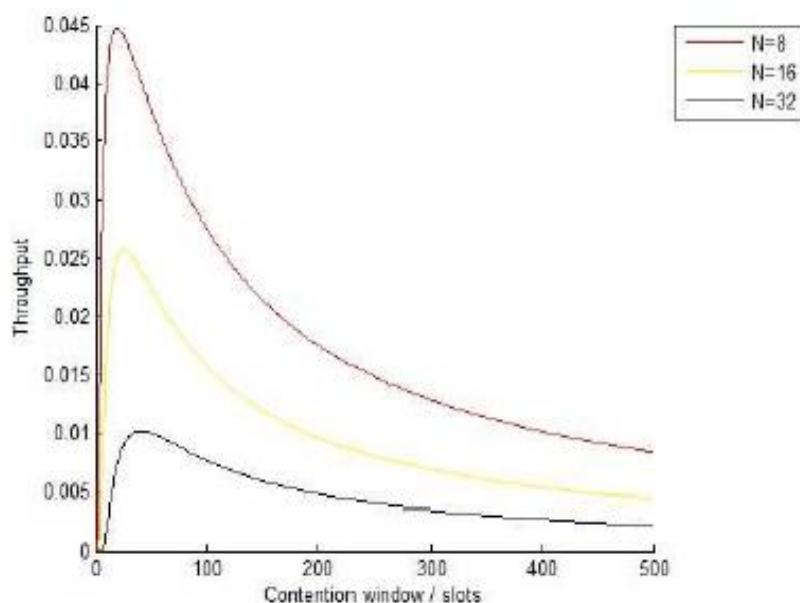
Εικόνα 5.8: Επίδοση vs *contention window/slots για το σενάριο 1 για διαφορετικό αριθμό κόμβων*
για κανάλι 80 kbps

Στην περίπτωση του καναλιού των 80 kbps η επίδοση του συστήματος βελτιώνεται κατά πολύ καθώς δεν μένει αχρησιμοποίητο εύρος ζώνης.

Η βέλτιστη τιμή για το contention window (CW) για διαφορετικό αριθμό κόμβων φαίνεται στον πίνακα 5.7:

Πίνακας 5.7: *Η βέλτιστη τιμή Contention Window για διαφορετικό αριθμό κόμβων για το σενάριο 2*

Number of nodes (N)	Throughput	Optimal Contention Window
8	0.0447	21
16	0.0256	28
32	0.0101	45

Παρατηρώντας τις παραπάνω εικόνες και τους παραπάνω πίνακες προκύπτει ότι όσο ο αριθμός των κόμβων στο σύστημα αυξάνει, η επίδοση του συστήματος μειώνεται ενώ η βέλτιστη τιμή του contention window αυξάνει. Επίσης από τη **Β** περίπτωση φαίνεται και η επίδραση του εύρους ζώνης του καναλιού στην επίδοση του συστήματος. Αν το εύρος ζώνης του καναλιού είναι κατά πολύ μεγαλύτερο από το απαιτούμενο από τις εφαρμογές, η επίδοση του συστήματος μειώνεται.

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Abbreviations

DC	**D**irect **C**urrent
AC	**A**lternating **C**urrent
LV	**L**ow **V**oltage
HV	**H**igh **V**oltage
DoE	**D**epartment **o**f **E**nergy
DG	**D**istributed **G**eneration
PLC	**P**ower **L**ine **C**ommunication
C&C	**C**ommand and **C**ontrol
BPL	**B**roadband over **P**ower **L**ine **t**echnology
OSI	**O**pen **S**ystem **I**nterconnection
PHY	**PHY**sical
MAC	**M**edia **A**ccess **C**ontrol
SCADA	**S**upervisory **C**ontrol and **C**ontrol **A**cquisition
RTUs	**R**emote **T**erminal **U**nits
PLCs	**P**rogrammable **L**ogic **C**ontrollers
IEDs	**I**ntelligent **E**lectronic **D**evices
MTU	**M**aster **T**erminal **U**nit
PID	**P**roportional **I**ntegral **D**erivative
GUI	**G**raphical **U**ser **I**nterface
QoS	**Q**uality **o**f **S**ervice
SYM	**S**ynchronous **M**odular **M**eter
SSNI	**S**ilver **S**pring **N**etworks
LED	**L**ight **E**mitting **D**iode
DAS	**D**istribution **A**utomation **S**ystems
FDIR	**F**ault **D**etection **I**solation **R**estoration
DA	**D**istribution **A**utomation
CML	**C**ynchronous **M**inutes **L**ost
ONR	**O**ptimal **N**etwork **R**econfiguration
IVVC	**I**ntegrated **V**olt **V**AR **C**ontrol
RAS	**R**emedial **A**utomation **S**chemes
DSM	**D**emand **S**ide **M**anagement

DR	**D**emand **R**esponse
LM	**L**oad **M**anagement
AM	**A**larm **M**anagement
ISA	**I**ndustry **S**tandard **A**rchitecture
MV	**M**edium **V**oltage
VoIP	**V**oice **o**ver **IP**
DLC	**D**ata **L**ink **C**ontrol
AMR	**A**utomated **M**eter **R**eading
AMI	**A**dvanced **M**etering **I**nfrastructure
RF	**R**adio **F**requency
NB	**N**arrow **B**and

Symbols

L	packet size	bits
T_p	packet transmission time	sec
T	interarrival time	sec
N	number of packets arriving during 24h	
D	data arriving during 24h time	
B	data rate	bits/sec
μ	mean value	sec
$\sqrt{\sigma}$	standard deviation	sec
λ	rate of the exponential distribution	1/sec
$E(T)$	expected value of the interarrival time	sec
S	throughput	bits/sec
P_s	the probability of successful transmission	
τ	the propagation delay	sec
I	the constant frame overhead	sec
$\overline{Y}$	the average winner backoff time	sec
I'	the constant frame overhead for realistic traffic	sec

1. Introduction

1.1. Objective of this Thesis

As it will been explained in Section Development of the Smart Grid, Smart Grid will possibly play a dominant role in the future. But there are still numerous challenges to be solved (as it will be discussed in Challenges and Requirements for future Smart transmission Grids). More research is needed regarding all the aspects of the Smart Grid.

In this direction, an analytical model for the Medium Access Control (MAC) layer of a Smart Grid system has already been developed at the Chair of Telecommunications of TECHNISCHE UNIVERSITAT DRESDEN. Using this model, the system performance under greedy traffic conditions can be found and analyzed [37].

The objective of this Final Project is the expansion of that model under realistic traffic. Some possible Smart Grid applications are proposed and the performance of a Smart Grid system which includes these applications is analyzed in terms of aggregate throughput.

This task is mainly analytical, but the results will be also treated with MATLAB.

1.2. Document structure

This Final Project aims to a detailed analysis of a Smart Grid system under realistic traffic and in order to fulfill this, the following document structure will be used:

- **Introduction:**
  In the current Chapter a brief introduction in the Smart Grid is exposed and its development from the current grid is discussed. Furthermore, the HomePlug Command and Control (C&C) specification is presented.

- **Smart Grid Applications:**
  In this Chapter, at first, a description of possible Smart Grid applications, mainly based on literature research, is included. Additionally, an expression of Interarrival Time of packets in terms of Packet Size and Bandwidth is found and being implemented for the discussed applications. At the end, a formal mathematical model for each application is derived that describes the traffic that produces in the network.

- **Final Traffic Model:**
  The derivation of the final model which is a superposition of all found application models in both analytical and simulation way is the subject of this Chapter. This

final model describes the traffic produced in the system when all or some of the discussed applications are working.

- **Throughput Calculation:**
  A brief reference to the analytical model for the calculation of the system throughput under greedy conditions that is already developed at the Chair for Telecommunications of TECHNISCHE UNIVERSITAT DRESDEN is given. Afterwards, a formula that calculates the throughput of the system under realistic traffic is being derived.

- **Results:**
  This Chapter presents the results of the Matlab simulations through diagrams that will be analyzed. The performance of a system, with all or some of the presented applications working, is studied in terms of aggregate throughput.

- **Conclusions:**
  Conclusions from previous chapters will be presented.

1.3. Smart Grid

1.3.1.   The history of the Electrical Grid

The development of the modern Electrical Grid started about a century ago in most industrialized countries and it has progressively evolved from the initial plan of Local DC Low Voltage (LV) networks, to the three-phase AC High Voltage (HV) grids and finally to the modern bulky interconnected networks with different voltage levels and a plethora of complicated electrical components [1].

A typical Electrical Grid transfers electricity from various energy suppliers to commercial and industrial consumers [2]. The main services of an Electric Grid are: bulk generation and energy transmission, distribution and consumption. In other words, electricity is generated by power plants, using other forms of energy, either renewable (wind, sun, hydro, geothermic, etc.) or non-renewable (coal, oil, natural/bio gas, nuclear) and is carried over long distances through an interconnected transmission HV network. Then the electricity is provided to the customers via distribution transformers. The electricity consumption takes place in a variety of environments, for example in houses, commercial buildings, industries etc. [4]

Figure 1.1 shows a general layout of a typical electricity network.
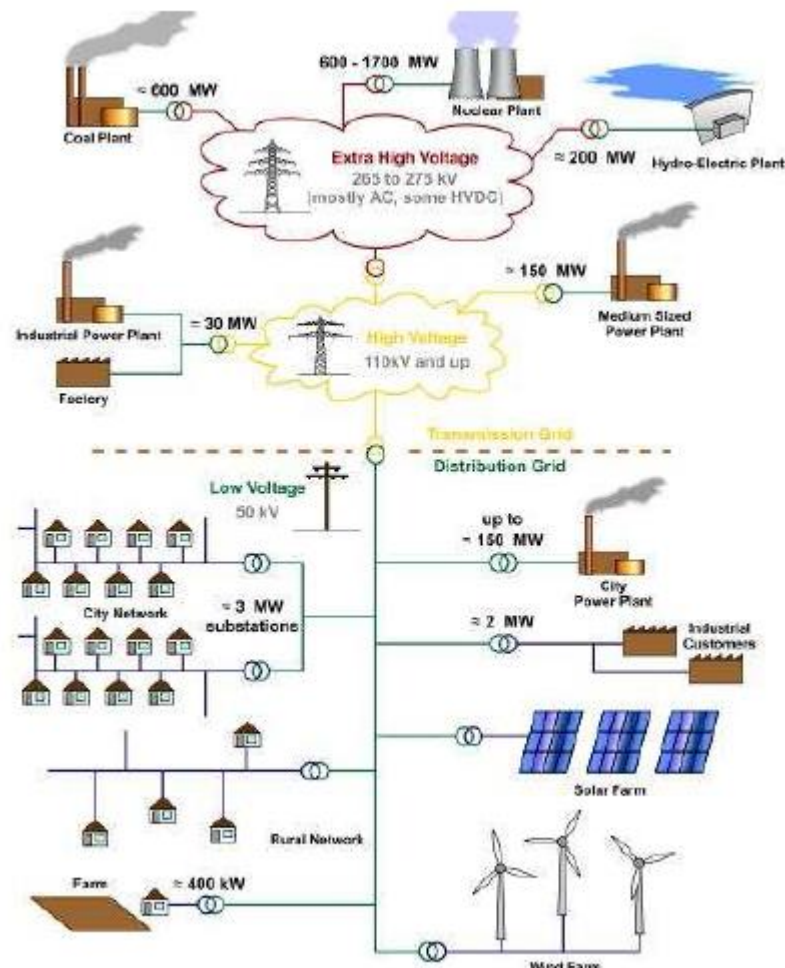
Figure 1.1: *General layout of electricity networks* [2]

1.3.2. Development of the Smart Grid

Nowadays, the huge demand of electricity supply in combination with the complicated structure of the traditional Electric Grid have created serious problems such as blackouts, voltage drops, overloading and waste of environmental sources. Consumers, markets and the emergent need of environmental protection (as the world's total CO_2 emissions grow in an accelerating pace) create new challenges and needs, with which the existing grid cannot cope. In order to overcome these problems, the traditional Electric Grid is currently evolving into a next generation grid, called *Smart Grid*. Generally, this new type of intelligent grid is described with the terms IntelliGrid, GridWise, FutureGrid, etc. [1]. The use of information technologies, communication systems and power electronics transform the electricity transmission and distribution industry.

1.3.3. Definition and Expected Benefits of the Smart Grid

The term **Smart Grid** has no exact definition. In the relevant literature there in a number of different descriptions, for example the following:

- The European Technology Platform defines Smart Grid as follows: 'A Smart Grid is an electricity network that can intelligently integrate the actions of all users connected to it- generators, consumers and those that do both- in order to efficiently deliver sustainable, economic and secure electricity supplies'[5].

- According to U.S. Department of Energy (DoE), a Smart Grid uses the digital technology to improve the reliability, security and efficiency (the economic as well as the energy) of the electric energy system- from the bulk generation, through the transmission systems, to the consumers- and reduce carbon emissions [1].

In brief, the term Smart Grid refers to a completely modernized system of electrical energy, which observes, protects and optimizes the function of its interconnected components, from end to end. It is a complex network of networks that aims to enhance the efficiency and reliability through automatic control, high power converters, modern structure communications, sensor technologies and modern management techniques based on the optimization of energy demand, the availability of energy etc. The system includes a number of electrical generators, which distribute electricity to industrial users, to home automation systems, energy storage facilities and final consumers, through the high- and low voltage distribution systems. The Smart Grid is characterized by two-way management of electricity and information, in order to create an automated, widely distributed energy delivery network. It integrates the advantages of decentralized computing and communications to transfer real-time information, aiming to balance the supply and demand of electricity.

The transition to the Smart Grid is imminent not only because today's grid is aging, inadequate and outdated and thus in need of modernization, but also due to the substantial expected benefits of Smart Grid [6], [7]:

- **Reliability:** It improves the reliability and the quality of energy, by diminishing the number of interruptions and power quality disturbances and reducing the frequency and duration of power outages.

- **Economics:** It mitigates the price of electricity through the interaction of the demand side of the market (consumers) with the supply side (suppliers).

- **Efficiency:** The efficiency of the system is enhanced by reducing the cost to produce, deliver, and consume electricity. Smart Grid also increases the capacity and efficiency of existing Electrical Networks.

- **Environmental protection:** By allowing customers to purchase cleaner, lower-carbon-emitting energy, it promotes a more evenly distributed deployment of

renewable energy sources, and provides access to more environmental-friendly power generation.

- **Security:** It reduces the probability and the consequences of manmade attacks and natural disasters to the electrical supply.

- **Safety:** Smart Grid lowers the number of injuries and loss of life from grid-related events

- **Customer benefits**: By enhancing customer choice to reduce consumption-cost in response to prices.

Figure 1.2 gives a general layout of Smart Grid:
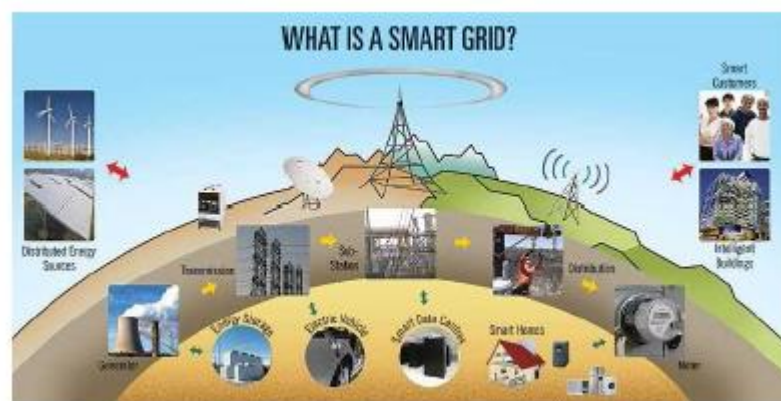
Figure 1.2: *General layout of Smart Grid [3]*

1.3.4.   Challenges and Requirements for future Smart transmission Grids

In order these benefits to be achieved, Smart Grid is expected to have the following characteristics [1], [10]:

- **Self-healing**: It should allow preventive maintenance and self-repair in cases of disturbances of the system, namely without the intervention of technicians. It automates the maintenance and the functionality of the electric grid in order to enhance its security and minimize consumer impact.

- **Digitalization**: Two-way fast digital communications will be required throughout the smart grid, between and among the utility's and consumers' devices, in order to achieve fast and reliable measurements, sensing, monitoring, communication, control, and protection. Wired and wireless telephone, fiber optics, power line carrier, satellite communications and Internet are options for the communications that can be used in smart grid.

- **Flexibility**: It should be able to expand and develop following any new, innovative and progressive technology. It also should be adaptive to the currently weather conditions and geographical locations. Furthermore, it should provide multiple control strategies for the coordination of decentralized control schemes among substations and control centers

- **Interoperability:** The efficiency and the effectiveness of the whole system mainly depend on the interoperability of the infrastructure. The successive function of the Smart Grid presupposes the existence of common and interoperable standards for the interconnection of both energy and communications.

- **Intelligence**: Intelligent technologies and human expertise will be incorporated into the Smart Grid in order to interconnect distributed generation (DG), provide automation and optimization to the distribution system and realize customers' needs. That means, that intelligence and control for all the system, from generation to the meter on the customer's side are required.

- **Resiliency:** The grid should be able to provide electricity to the customers with security and reliability despite any internal or external danger. It should be able to cope with attacks and natural disasters with rapid restoration capabilities.

- **Sustainability**: For the Smart Grid, sustainability means sufficiency, efficiency and environment-friendliness. The electricity demand should be satisfied through both the implementation of renewable sources such as solar/wind/geothermic energy and the increase of energy storage. Additionally, the technologies used should provoke less pollution and reduce carbon emissions.

- **Customization:** The design of Smart Grid should be customer-oriented with no loss of its functions and interoperability. It aims to provide more consuming options to the customers with the best possible quality in the lowest possible price. The customers are no more uninformed and nonparticipating but on the contrary they are active through board penetration of demand response.

1.4. Comparison of Smart Grid with current Electric Grid

Table 1.1 contains the basic differences between the Smart Grid and its ancestor Electrical Grid that indicates the evolution of the grid and the new services that it provides.

Table 1.1: *Table of the features of the existing grid in comparison with the Smart Grid [2]*

Existing Grid	Smart Grid
Electromechanical	Digital
One way communication	Duplex communication
Central production	Distributed generation
Few Sensors	Sensors everywhere
Damages and blackouts	Adaptability
Restricted Control	In deep control
Few customer choices	A lot of customer choices
Manual Healing	Self-healing
Manual observation	Automatic Observation

1.5. HomePlug

Power Line Communications (PLC) technology is an attractive alternative for data communications and can offer commercially viable communication solutions. In order its wider installation and use to be achieved; it is important standards acceptable to all participants to be developed. Groups of companies forming industrial alliances, as well as individual companies, have developed PLC specifications that aim to promote the widespread adoption of PLC technologies sponsored by these companies. In this direction, a group of companies from all over the world and from various sectors formed HomePlug Powerline Alliance. As it is reported in its official site [8], 'The Alliance's mission is to enable and promote rapid availability, adoption and implementation of cost effective, interoperable and standards-based home powerline networks and products'.

HomePlug Command and Control Specification (HomePlug C&C) has been defined by HomePlug Powerline Alliance in order to 'address the need of reliability for a robust and immune from many types of line interference system'[9]. The HomePlug C&C specification creates a standard for low bandwidth, low cost and highly reliable Powerline Communications (PLC) applications for residential and industrial environments. Such devices from different manufacturers, designed for different applications and using different protocol layer implementation will be functioning all together and be connected to each other as well as they can be easily developed and installed.

This technology is complementary to the HomePlug Powerline Alliance's existing HomePlug 1.0 as well as the new HomePlug AV and BPL standards.

HomePlug C&$C has been designed according to the OSI-7 layers reference model. A PHY and MAC specification has been already released in 2007, while specifications for the Network and Host layers are being drafted currently. This model is depicted in Figure 1.3 [9].
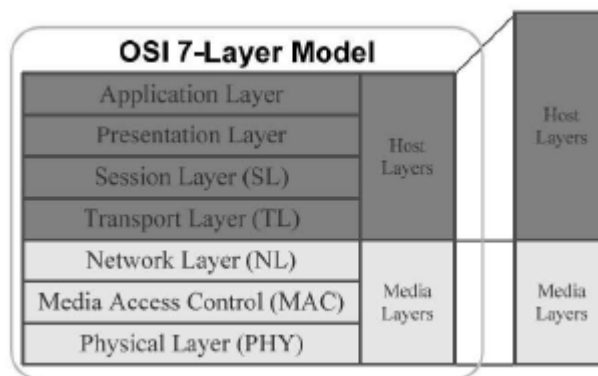
Figure 1.3: *HomePlug based on OSI-7 layers reference model*

- **PHY layer**
  The first layer is the PHY layer that provides the physical link between communicating network systems by defining the electrical, mechanical, procedural, and functional specifications for its activating, maintaining and deactivating. It is based on differential code shift keying spread spectrum modulation.

- **Media Access Control (MAC) Layer**
  The Media Access Control (MAC) Layer provides data services and channel access control mechanism that make it possible for many nodes and devices to share the power line media and to communicate avoiding any mutual collision using CSAMA/CA with adaptive back off.

- **Network Layer**
  The Network Layer will provide Internet-working and Intranet-working data services as well as Management services.

- **Host Layer**
  Host layer will ensure full interoperability between different devices from different manufacturers. Transport and Session layers profiles will be included that provide a common description language to define devices in terms of services supported, service properties and actions, and sub-devices as well as implements device profiles and interfaces lower layers' services.

HomePlug C&C features:

- HomePlug C&C is the ideal solution for command and control for home appliances, security and home automation.
- HomePlug C&C is a low cost solution that can be incorporated in any home device
- HomePlug C&C devices support plug and play so that connecting these devices to each other, is as easy as plugging in to the electrical socket.

Some applications that follow HomePlug C$\&$C specification:

- Smart Meters
- Demand Response and Demand Management
- Street light control
- Remote command and control-Home Appliances Automation
- Industrial Automation
- Sensors and Life Safety Devices
- Monitoring Security and Safety including remote access and control via the internet

2. Smart Grid Applications

2.1. Description of possible Smart Grid Applications

In this section ten Smart Grid Applications are proposed as possible applications that may coexist in a Smart Grid System. These applications are: SCADA, Software download/upgrade firmware, Street lighting and traffic control, Distribution Automation and traffic protection, Load Management, Alarm Management, Video Surveillance, Operational Telephony, Smart Meters and On demand Meter Reading. A brief description of each one of them, based mainly on literature study, follows:

2.1.1. SCADA

SCADA stands for Supervisory Control and Data Acquisition and it refers to systems/applications that are used to monitor the electrical network and control the automated devices [4]. These systems are responsible for the transfer of data between a SCADA central host computer, a number of Remote Terminal Units (RTUs) and/or Programmable Logic Controllers (PLCs) and the central host and the operator terminals [10]. It commences with measurement of the data (such as where a leak on a pipeline has occurred) by specific devices in the field of application and collection of them via intelligent electronic devices (IEDs), then transferring these data to a master station (alerts the master station that a leak has occurred) to implement the necessary processing and control algorithms (determining if the leak is critical). The results of processing are displayed on a number of operator monitoring screens in a logical and organized fashion, while the control actions are conveyed back to the field of application in real time [11].

Namely SCADA is referred to the combination of telemetry and data acquisition. By telemetry is defining the technique used for measuring the data (voltage, current, speed, etc.) from different locations in the real-time process and transferring it to the IEDs such as remote terminal units (RTUs) or PLCs in another location through a combination circuit. Data acquisition refers to the method used for accessing and collecting the data from the devices being controlled and monitored, and to be forwarded to a telemetry system ready for transfer to the various sites. The data may be analog or digital gathered by sensors such as ammeters, voltmeters, speedometer, and flow meter. It can also be data to control equipment such as actuators, relays, valves, and motors [11].

A SCADA system consists of [10], [11]:

1. one or more field data interface devices (RTUs, PLCs, etc.), where data are being gathered from different devices and stored waiting for a request from the master station to transmit the data,

2. a communications system that transfers data between field data interface devices and control units and SCADA central host through a variety of communication channels, including radio links, leased lines, and fiber optics,

3. a central host computer server or servers (sometimes called a SCADA Center, master station, or Master Terminal Unit(MTU)), the main functions of which are: making the communication, gathering data, storing information, sending information to other systems, processing the data gathered by remote stations to generate the necessary actions,

4. standard and/or custom software systems that are provided to the SCADA master station support the communications system, and monitor and control remotely located field data interface devices.

In the Figure 2.1 the structure of a typical SCADA system is shown:
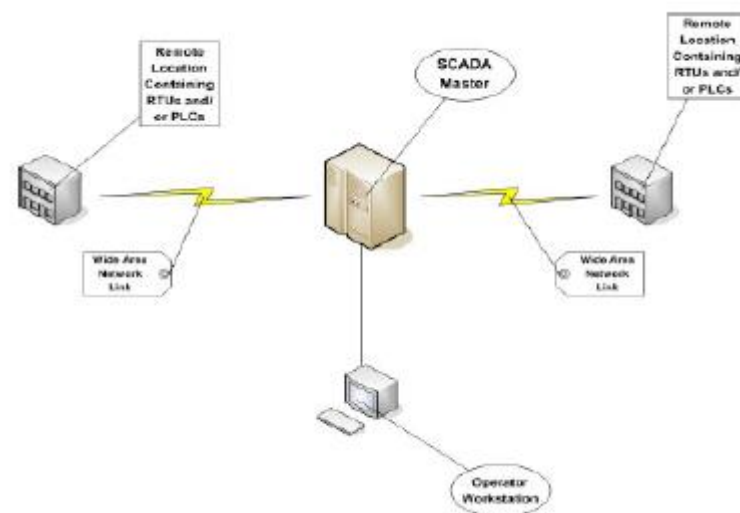

Figure 2.1: *A typical SCADA system*

Characteristics of the SCADA Systems [10]:

1. self-diagnostics and easily maintained

2. capability of arithmetic functions implementation

3. easy to program and reprogram

4. facility of communication with other controllers or a master host computer

5. the ability of PLCs to move past simple control to more complex schemes as

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Proportional/integral/derivative (PID) control

6. capability of graphical user interface (GUI) and visual display of system Status

This application is a grid critical application, namely it may require a higher QoS not based upon its operating requirements, but based upon its importance in the overall system. According to [4], in order about 20 devices to be controlled per data concentrator at 200 bytes per message at 200 messages (request and response) an hour data rate about 1800 bits/sec is demanded.

2.1.2. Software download/upgrade firmware

The information technology domain employs different decision and control software applications, such as firmware embedded in the intelligent electronic devices(IED), applications that are integrated in automation systems and control centers and also enterprise back office software. These software applications aim to provide intelligence in the Smart Grid and so they play a dominant role in its development. Few of them have already been developed, while the majority of software applications are still in evolution. Smart Grid software applications are in a never-ending state of flux as the expectations and the needs of its different users are always changing. Thus, new software always is being evolving and upgrading [12].

Download and upgrade of software for all the devices in the Smart Grid is essential. For example, as authors in [18] analyze, Modern Smart Meters are Embedded Systems, running software on a microcontroller platform and update of Smart Meters' Software is needed in order new features to be added or errors to be corrected. Additionally, a Secure Software Download mechanism is strongly needed as Security plays a major role in such applications. Thus, in [13] the SYM specification, that offers Remote Software Download mechanisms and has developed by the German tLZ working group, is investigated.

As it is reported in [4], Software download is not a time critical application. Namely, it can be done in the background and even be interrupted and continued later on. Different devices are not needed to be upgraded concurrently. In most cases, each device stores two software loads: one active and one inactive and when an update take place, the inactive one will be replaced by the new version. It is possible that the inactive program becomes the active one, and vice versa, by triggering a switch.

In [4] some interesting features of this kind of application are given. Upstream data per node are 10kilobytes-100kilobytes, while download data per node are 100kilobyte-10megabyte. Permissible latency is at most 24hours. Furthermore, assuming 100kilobyte-10megabyte per software load over 24 hours results in 9-900 bits per second throughput per device.

2.1.3.   Street lighting and traffic control

A Street lighting and traffic control system is a telemanagement system that enables the lighting system to automatically react to external parameters like weather circumstances, remaining daylight level, accidents or traffic density. 'Smart city' devices help the city to provide the right level lighting needed by time of day, season or weather conditions [4].

It is responsible not only to control the street lights, but also to monitor the age and condition of every street lamp. Thanks to the bidirectional communication that characterizes this application, it is used for monitoring, control, metering and diagnostic applications in order to save energy, reduce maintenance costs and improve the reliability of the system [4]. Each networked street light or traffic signal can deliver useful information to operators, including when they're on or off, and of course, whether they're working or not so as to be replaced before traffic problems due to loss of street lights occur. In addition, 'intelligent street lights and traffic signals' reduce the potential for electrical shocks to residents and employees because equipment faults are automatically detected and relayed.

As it is referred in [14], Silver Spring Networks (SSNI), the smart grid networking company, will try 'smart lights' and other 'smart city' devices in Paris in order to reduce the city's lighting energy consumption by nearly one-third by decade's end. 'Paris wants to reduce its overall lighting energy consumption by 30% from 2004 levels by 2020, through a combination of more efficient lighting like LEDs and smarter control systems.' They intend to provide the unified wireless networking platform to link both street lights and traffic signals for increased operational efficiency that will lead to reduced street lighting costs.

As Echelon states: 'the city of Oslo reduced energy consumption by 62% with Echelon's Smart Street Lighting Solution. In China, 500.000 smart streetlights using Echelon power line technology will come online by 2014, with an expected energy reduction of 55%.Smart street lighting is often just the first step to a smarter city, for example, Quebec added a bus lane control system to Echelon's Street Lighting Solution and eliminated the cost of a second infrastructure' [4].

This application is not time critical. A data rate 25 bits per second is necessary to control a group of 32 street lights. Latency for control commands can be up to 300 seconds.

2.1.4.   Distribution automation and traffic protection

Distribution automation systems (DAS) are responsible for the automation of remote switching, operation and control of the distribution network.

These systems perform:

- **Fault Detection, Isolation and Restoration (FDIR)**

  FDIR is a DA process that performs remote switching actions in order to rapidly and automatically restores a service to as many customers as possible following an outage caused by a permanent feeder fault in order to reduce consumer minutes lost (CML). It supports remote tele-measurements within the local grid in order to protect the grid from perturbations by isolating only the faulted part from the rest of the network and in this way as much of the network as possible is still in operation and the power system remains stable. Protection devices operate autonomously, without the need to control them. Namely, the major functions that FDIR performs are [16] [17]:

1. detection of the fault,
2. location of the damaged portion of the feeder between two remote controlled line switches
3. disconnection-isolation of the damaged part of the feeder or area by opening remote controlled line switches
4. re-energization of the undamaged potions of the feeder via the primary feeder source and one or more backup sources using remote controlled tie switches so as to reduce overall CML by reducing restoration times to seconds or minutes, instead of hours.
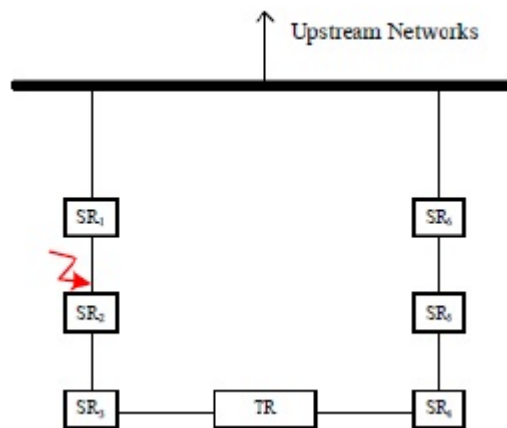
Figure 2.2: *Basic feeder configuration with a faulted feeder section between SR1 and SR2 [16]*

Thus FDIR directly accomplishes the 'self-healing' characteristic off the smart grid and improve overall network reliability.

- **Dynamic Network Reconfiguration**

  With Optimal Network Reconfiguration (ONR) grid reconfiguration through (automated) switching actions is possible in order to achieve power flow optimization, minimization of losses and prevention of component overloading. In brief, ONR identifies ways in which the electric utility can reconfigure an

interconnected set of distribution feeders to accomplish one or more of the above mentioned objectives. In this way, distribution network efficiency, capacity and component lifetime will increase [16] [17].

- **Planned Islanding**

  In the distribution system there are some temporarily isolated ('islanded') portions that are being powered by distributed energy resources owned by independent power producers. This intentional islanding of selected portions of the distribution system is referred as 'microgrid' operation. DAS are responsible for monitoring and control of these portions. As a result, grid reliability is enhanced and high power quality is provided to customers with sensitive loads. Additionally, in cases where backup sources are heavily loaded planned islanding is responsible for power restoration [17].

- **Integrated Volt-VAR Control (IVVC)**

  'IVVC is an advanced DA function that determines the best set of control actions for all voltage regulating devices and VAR control devices to achieve a one or more specified operating objectives without violating any of the fundamental operating constraints (high/low voltage limits, load limits, etc.)' [17].

In brief some other functions of DA Application are: data gathering along with data consistency checking and correcting, integrity checking of the distribution power system model, periodic and event-driven system modeling and analysis, current and predictive alarming, contingency analysis, pre-arming of RAS(remedial automation schemes) and coordination of emergency actions in distribution, pre-arming of restoration schemes and coordination of restorative actions in distribution and logging and reporting.

As it is referred in [22] a typical control message size for DA applications is 150-500 bytes and the data rate would be greater than 18kbps if it is assumed that there are 15 such field devices to control (typical number of devices per 1000meters) with the most stringent latency requirement of less than 1 second per message (i.e., 150bytes * 8bits/bytes * 15 / 1sec~\sim18kbps).

2.1.5. Load Management, DSM

The generation and the consumption of electricity must be balanced. Until now, generation was easily be controlled, while loads have traditionally been a passive part of a grid. Nowadays, Load Management and Demand Response (DR), as demand-side technologies, play an increasingly important and determining role in the energy efficiency of power grids.

Load Management is a smart grid application responsible for balancing the supply of electricity on the network with the electrical load in order to optimize, according to the behavior of each different type of customers, energy production costs, enhance energy

utilization or system reliability, or to match utilization to environmental factors [18]. In other words, 'it refers to the adjustment of demand to match supply and can be understood as a client's response to demand-side management' [20].

With Demand Response (DR) application consumers have access to real time electricity pricing information and can respond to price signals by changing their energy consumption through a two-way communication system. Otherwise, as it is defined in [20] DR is "a tariff or program established to motivate changes in electric use by end-use customers in response to changes in the price of electricity over time, or to give incentive payments designed to induce lower electricity use at times of high market prices or when grid reliability is jeopardized".

Furthermore, customers can adjust their demands through setting the operating time of some of the home appliances with energy storage feature such as heaters based on the real time prices to shift their consumptions and save cost.

For load management applications, e.g., direct load control, data rate requirements will depend on the number of customers participating in load control programs. If we assume that 500customers participate in a load control program, and each message is of 64 bytes in size with at most 5-second latency requirement, the required data rate would be more than 50 Kbps (i.e., 64bytes *8bits/bytes * 500 / 5sec~\sim 51.2 kbps) [22], [19].

According to reference [4] the demanded bandwidth for this application is 2000Kbits/sec and its maximum latency 1 sec.

2.1.6. Alarm Management

Alarm management in smart grid is an application that detects an event that requires attention of the entire control system and transmits that information-alarm to the system in order to prevent any undesirable events. An alarm situation may have various causes, i.e. failure of a component within the local grid or the remote control system or any anomaly within the grid [4].

In [21] the ISA-18.2 Alarm System Management Lifecycle is provided. The Figure 2.3 depicts the ISA-18.2 Standard for Alarm Management:
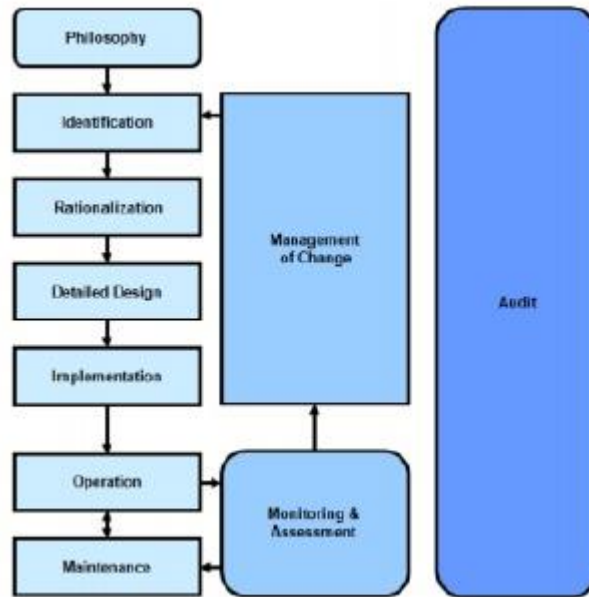
Figure 2.3: *ISA-18.2 Alarm System Management Lifecycle [21]*

Brief explanation of the steps of the Alarm Management's Lifecycle according to ISA-18.2 Standard:

- **Philosophy**

  The usual first stem of Alarm Management is the development of an alarm philosophy, namely, a comprehensive design and guideline document for the next lifecycle stages that defines what exactly is an alarm.

- **Identification**

  Various processes like P\ID reviews, process hazard reviews, layer of protection analysis and environmental are used in order potential alarms to be identified. It is helpful for the next stages to document the cause, potential consequence, and the time to respond for each identified alarm.

- **Rationalization**

  Each potential alarm is testified in order to be proven if it is in fact an alarm or not according to the alarm philosophy. Furthermore, alarm's attributes, such as limit, priority, classification, and type, are defined and saved in a Master Alarm Database.

- **Detailed Design**

  According to the philosophy document and the rationalization the alarm is designed using the information saved in the Master Alarm Database for the configuration of the system.

- **Implementation**

  In this stage the alarms are put into operation through training, testing and commissioning.

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- **Operation**

  Now, the alarm notifies the operator with the abnormal behavior.

- **Maintenance**

  This process places the alarm out-of-service, namely, in the maintenance stage the alarm does not indicate the problematic component.

- **Monitoring and Assessment**

  Monitoring and Assessment include comparison of the alarm system performance with "the stated performance goals in the philosophy", as well as identifying of "nuisance" alarms (alarms that cannot stop after the fault is corrected or annunciate with no reason, etc.).

- **Management of Change**

  Addition of alarms, changes to alarms, update of Master Alarm Database and deletion of alarms are some functions that can be performed in the stage of Management of Change.

- **Audit**

  Audit is focused on the review of the performance of the alarm system and the achievement of its improvement. The alarm philosophy document may need to be modified to reflect any changes resulting from the audit process.

This application according to [4] needs data rate at around 9.6kbit/sec and its maximum latency is 30 sec. The traffic type that produces is random and it has priority in the grid.

2.1.7.   Video Surveillance

The Electrical Grid has a lot of times suffered from robberies. Copper cables or any other equipment that can be sold sometimes have been stolen causing at least temporary problems to the electricity transmission or to communications. In Smart Grid, live video surveillance represent a viable deterrent for such attacks in substations and gives higher security to all range of public or private facilities, either by locally or remotely monitoring the video sequences captured in the areas covered by it. Using video cameras, sensors, image processing units and network devices, which allow the capture, processing and transport of the surveillance data it is possible to have real-time video feeds from each substation as well as video recording and archiving [23].

However, video monitoring requires significantly more bandwidth than the low-bandwidth communications used to enable SCADA. Generally, video transmission is bandwidth intensive with the bandwidth required varying widely base on resolution and frame rate requirements. For example, as it is referred in [24], 'for a SXVGA (high definition) transmitting 30 frames per second with minimal compression, the bandwidth requirement is \sim 47Mbps per camera. In the case of this project, the capturing/transmitted frame rate and video resolution will be limited, the video capturing will be event triggered (alarm indication, door opening…) due to the limited network bandwidth. Thus, the video surveillance is restricted to surveillance of MV/LV sites and equipment, Furthermore, it is required latency-sensitive and always-on connectivity in order to enable real-time monitoring [4], [24].

The data rate acquired for this application, according to [4], is at around 15-128Kbit/sec and its maximum latency is 1 sec. The traffic type that produces is random and it has not priority in the grid.

2.1.8. Operational Telephony

Operational telephony provides a direct bidirectional audio connection to the network operation center. In this case, it will be a VoIP connection over a DLC network [4].

In reference [4] it is reported that this application might have bandwidth 8kbit/s, its maximum latency is 0.5sec and the traffic type produced by this is random.

2.1.9. Smart meters

A smart meter is an advanced energy meter (usually an electrical meter but it can also mean a device measuring natural gas or water consumption) that identifies energy consumption of a consumer in more detail than a conventional meter and securely communicates this information (including values of voltage, phase angle and the frequency) to the utility company by two way communication systems for monitoring and billing purposes (telemetering) [4], [25].

Smart meters are able not only to communicate and execute control commands remotely as well as locally, but also to control and monitor all home appliances and devices at the customer's premises. Additionally they collect diagnostic information about the distribution grid, home appliances and communicate with other meters in their reach. They can measure electricity consumption from the grid, support decentralized generation sources and energy storage devices, and bill the customer accordingly. Smart metering can also provide other customer services such as optimal energy consumption based to real time price signals and the willingness of customer to reduce loads, time-of-use rates, prepay opportunities and the control of smart applications for demand reduction. In addition, the

utility companies can detect unauthorized consumption and electricity theft in view of improving the distribution efficiency and power quality [25].

A smart meter system employs several control devices, a lot of sensors to identify parameters and devices to transfer data and command signals. Depending on not only the environment and the location where smart meters are found and function but also to their efficiency power quality, security features, bandwidth etc., the communication technologies used are varying: cell and pager networks, Bluetooth, satellite, licensed radio, combination [25],[27].

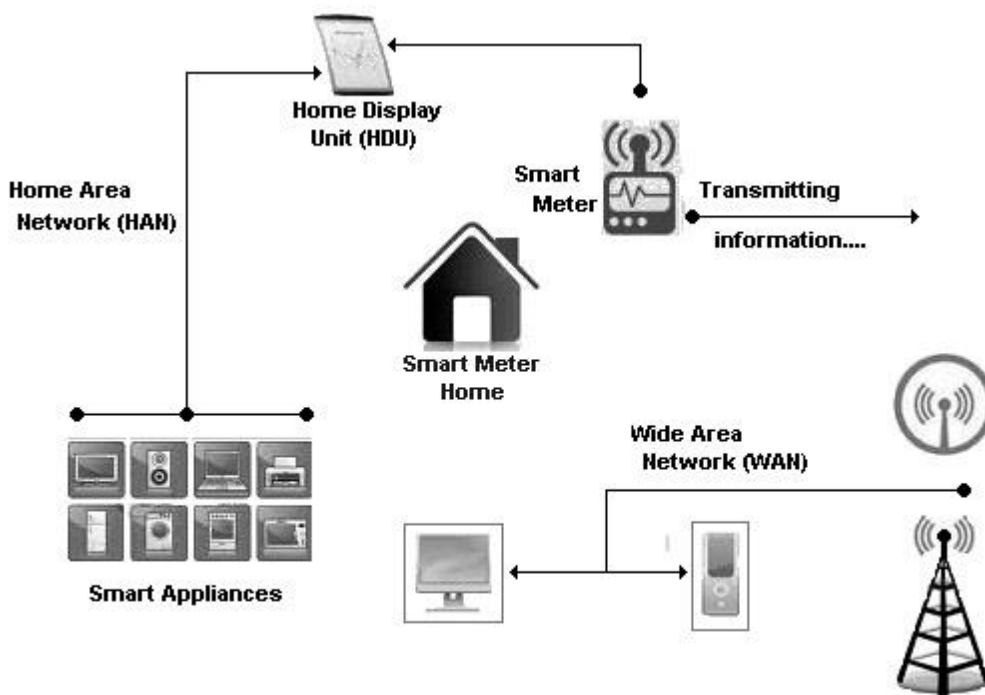Figure 2.4 depicts a general smart meter layout:

Figure 2.4: *Smart meter diagram [26]*

Similar meters, usually referred to as interval or time-of-use meters, have existed for years, but Smart Meters usually involve a different technology mix, such as real-time or near real-time sensors, power outage notification, and power quality monitoring. These additional features are more than simple automated meter reading (AMR). They are similar in many respects to advanced metering infrastructure (AMI) meters [4], [25].

AMR stands for Automatic Meter Reading, namely is a remote reading system based on an advanced technology that permits utilities to read electronic meters, collect consumption, diagnostic and status data from them and transfer that data to a central database for billing, troubleshooting, and analyzing. Thus, there is no more need of periodic

trips of the utility providers to each physical location to read a meter and billing can be based on near real-time consumption rather than on estimates based on past or predicted consumption. Telephony platforms (wired and wireless), radio frequency (RF), or powerline transmission are the technologies that support AMR systems.

AMI An extension of the simpler AMR-system that just collected meter readings electronically and matched them with accounts is **AMI** that stands for Automated/Advanced Multi-Metering Infrastructure. AMI systems represent the networking technology of fixed network meter systems that add remote utility management in the feature of AMR. It is architecture for automated, two-way communication between a smart utility meter with an IP address and a utility company. Namely, as it is analyzed in [4], 'A future AMI scenario will allow energy service companies to provide demand management capabilities while also establishing new services that create value for energy consumers, network operators, metering operators and retailers. These services will at least include automatic meter reading, flexible and remotely programmable power control, remote (re)connection and disconnection and flexible tariff management.

Automated Meter Management (AMM) or Smart Metering is 'another expansion of remote system that includes possibility of performing technical measurements and functions and carrying out customer-oriented services via the system' [4]. The main difference between AMM and AMR solution is that with the first the utility company is able to manage its production according to the consumers' needs.

In [4] is stated that an AMR application requires bandwidth at around 5.3kbit/s. The maximum permissible latency is up to 8 hours for the collection of daily interval reads of individual meters. Upstream data per node are 2000-10000 bytes, while download data per node are 50 -400 byte. As it has already referred in the description of the 'On demand meter reading', which is a case of smart metering too, the maximum permissible latency is 1-5 seconds, upstream data per node are 100-500 bytes and download data per node are 50-100byte. The traffic produced by it is periodic, namely the meters in the network have to be read out periodically. The average number of smart meters (AMR/AMIAMM) in a subsystem is 150-200 with maximum 300 concentrators. Assuming that the frequency of reading out of the meters is 15 minutes (time interval=15 minutes), 96 data packages per day and per meter have to be collected. If 2kbytes are read out every 15 minutes, this results in a data rate 18bit/sec per meter. For 300 meters per station, we have 600 Kbyte every 15 minutes and thus 5,333kbit/s per station. That depends on the topology of the network.

Furthermore, in [2], it is assumed that the utility inquiries 625 smart meters per concentrator in a neighborhood and then the required data rate is 100bytes * 8bits/bytes * 625 / 5sec\sim 100kbps (latency requirement of less than 5$ seconds).

2.1.10.   On demand meter reading

A request of immediate parameters such as consumption, real-time pricing or the presence of power or other parameters can be served by on demand meter reading Smart Grid application.

In [4] some interesting features of this kind of application are given. Upstream data per node are 100-500 bytes, while Download data per node are 50 -100 byte. Permissible latency is around 1-5 seconds. In \cite{Referencepage2}, assuming that a typical meter message size is 100 bytes with latency requirement of less than 5 seconds and that there are 625 smart meters per concentrator in a neighborhood, the required data rate would be: 100bytes * 8bits/bytes * 625 / 5sec = 100 kbps.

2.2. Interarrival Time of each Smart Grid Application

2.2.1.   Expression of Interarrival Time in terms of Packet Size and Bandwidth

In this paragraph a way of calculation of the Interarrival Time of packets in a network is proposed.

Figure 2.5 depicts packets entering a network during a time interval, for example during 24h.
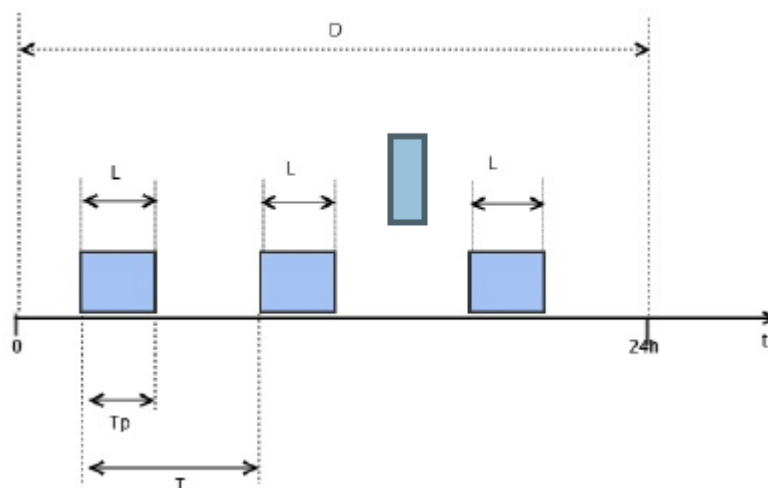

Figure 2.5: *Arrivals of packets during 24h*

Assuming that:

L(bits): packet size

T_p(sec): transmission time

T(sec): interarrival time

N: number of packets arriving during 24h

D(bits): data arriving during 24h

B(bits/sec): data rate

data rate could be expressed as the fractal of the data arriving during the specified time interval(24h here) divided by it:

$$B = \frac{D}{24h} \quad (2.1)$$

but the total amount of data arriving during 24h are the number of arriving packets during this time interval multiplied by the packet size of each packet (assuming that all the packets have the same packet size) :

$$D = N \cdot L \quad (2.2)$$

According to 2.1 and 2.2:

$$B = \frac{N \cdot L}{24h} \Rightarrow N = \frac{B \cdot 24h}{L} \quad (2.3)$$

The interarrival time (time interval passing between two arrivals of packets is:

$$T = \frac{24h}{N} \xrightarrow{2.3} T = \frac{L}{B} \quad (2.4)$$

Equation 2.4 gives an expression of the interarrival time in terms of packet size and bandwidth.

2.2.2. Computation of Interarrival Time of each Smart Grid Application

In this paragraph, mean interarrival time of each application is computed, using the equation 2.4 and data collected from [4], [22], [2] and referred in paragraph 2.1.

Table 2.1 contains the selected data from the above referred sources. Specifically, it contains possible values for the data rate and the packet size of each application.

Table 2.1: *Table of Smart Grid Applications' Datarate (kbps) and Total Packet Size*

#	Smart Grid Applications	Datarate(kbps)	Total Packet Size
1	SCADA	[1.8,9.6]	512 bits
2	Software download/upgrade firmware		
	upstream	32	[10kbytes,100kbytes]
	downstream	32	[100kbytes,10Gbytes]
3	Street lighting and traffic control	0.025	512 bits
4	Distribution automation and traffic protection	18	150-500 bytes
5	Load Management	50	512 bits
6	Alarm Management	9.6	512 bits
7	Video Surveillance	[15,128]	512 bits
8	Operational telephony	8	512 bits
9	Smart Meters		
	upstream	5.3	[2000, 10000] bytes
	downstream	5.3	[50, 400] bytes
10	On demand-reading		
	upstream	100	[100, 500]
	downstream	100	[50,100]

Observing the Table 2.1, it is obvious that for some applications the values of either data rate or packet size vary in an interval, while for other applications the values of both data rate and packet size, found in bibliography, are specific. This depends on the amount of data that were found in the relevant literature.

Equation 2.4 is implemented in both cases in order the interarrival time or the interval of the interarrival time to be calculated and the results are summarized in the Table 2.2:

Table 2.2: *Table of Smart Grid Applications' Interarrival Time*

#	Smart Grid Applications	Interarrival time (sec)
1	SCADA	[0.00533,0.2844]
2	Software download/upgrade firmware	
	upstream	[2.5,25]
	downstream	[25,2500]
3	Street lighting and traffic control	20.5
4	Distribution automation and traffic protection	[0.0666,0.2222]
5	Load Management	0.00102
6	Alarm Management	0.05333
7	Video Surveillance	[0.004,0.03413]
8	Operational telephony	0.064
9	Smart Meters	
	upstream	[0.37735,1.8867]
	downstream	[0.00943,0.07547]
10	On demand-reading	
	upstream	[0.008,0.04]
	downstream	[0.004,0.008]

However, in the first case, the 2.4 is implemented for both the under and upper bound of the intervals of values of either data rate or packet size. Afterwards, the mean value of these interarrival times is found, as well as the standard deviation.

According to [29], when a random variable X takes random values from a finite data set x_1, x_2... x_N, with each value having the same probability, its mean value and standard deviation are:

$$\mu = \frac{1}{N}\Sigma_{i=1}^{N} x_i \qquad (2.5)$$

$$\sigma = \sqrt{\frac{1}{N}\Sigma_{i=1}^{N} (x_i - \mu)^2} \qquad (2.6)$$

Table 2.3 contains the mean value and the standard deviation of the interarrival time of the applications for which the collected data were more:

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Table 2.3: *Mean value and standard deviation of interarrival time for applications with varying either data rate either packet size'*

#	Smart Grid Applications	mean value(sec)	Standard deviation(sec)
1	SCADA	0.1689	0.1156
2	Software download/upgrade firmware		
	upstream	13.75	11.25
	downstream	1262.5	1237.5
4	Distribution automation and traffic protection	0.1444	0.0778
7	Video Surveillance	0.019	0.015
9	Smart Meters		
	upstream	1.132	0.0001
	downstream	0.0424	0.0001
10	On demand-reading		
	upstream	0.024	0.016
	downstream	0.006	0.002

For the remaining applications with the specific values for their data rate and packet size the Equation 2.4 is implemented and the expectations of their interarrival times are selected in Table 2.4:

Table 2.4: *Interarrival time for application with specific values for both Datarate and Total Packet Size.*

#	Smart Grid Applications	Interarrival time (sec)
3	Street lighting and traffic control	20.5
5	Load Management	0.00102
6	Alarm Management	0.05333
8	Operational telephony	0.064

2.3. Derivation of formal mathematical model for the traffic produced by each application

The traffic produced by each application will be described as a distribution function with random variable the interarrival time of each application.

Concerning the applications in the Table 2.3, it could be assumed that a normal distribution with random variable the interarrival time of one of these applications could describe its traffic. This assumption is mainly based on the descriptions of these applications and the data found in the literature research. The interarrival time of an application can be any real number in the corresponding for each application interval shown in Table 2.2. So, the normal distribution, that is a function that tells the probability of a number in some context falling between any two real numbers, could be a good approximation for the distribution function of the interarrival time that describes the

traffic of each of these applications. The mean value and the standard deviation for each application have been already computed in the table Table 2.3} and are the parameters of the normal distribution.

According to [31], a random variable X is a normal random variable (or X is normally distributed) with parameters μ and $\sqrt{\sigma}$ if it has density function:

$$f(x) = \frac{1}{\sigma \cdot \sqrt{2\pi}} \cdot \exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right) \quad \text{for } -\infty \leq x \leq \infty \qquad (2.7)$$

This density is a bell shaped curve that is symmetric around μ that is depicted in 2.6:
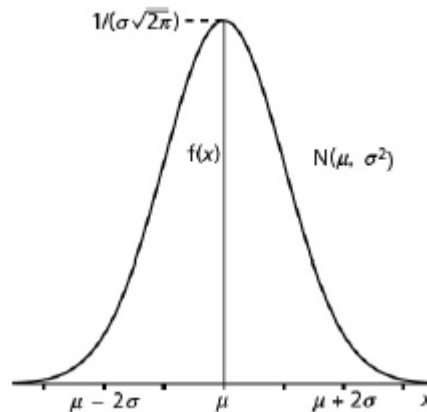

Figure 2.6: *Normal density function*

Thus, distribution functions 2.8- 2.16 describe the traffic produced by each application of Table 2.3. Below each expression of distribution function there is a normal probability plot as well as a plot of each probability distribution. The normal probability plot is produced by the command 'normplot' of Matlab and its is to graphically assess whether the data in X could come from a normal distribution. If the data are normal the plot will be linear [32]. The data are randomly produced by Matlab following however the according distribution (Equations 2.8-2.16). That's why there are some negative values in the x-axis, fact that it is not logical in our case because the data are interarrival times that could not be negative.

$$P_{\text{SCADA}} = \frac{1}{0.115555556 \cdot \sqrt{2\pi}} \cdot \exp\left(-\frac{(x-0.168888889)^2}{20.115555556^2}\right) \qquad (2.8)$$
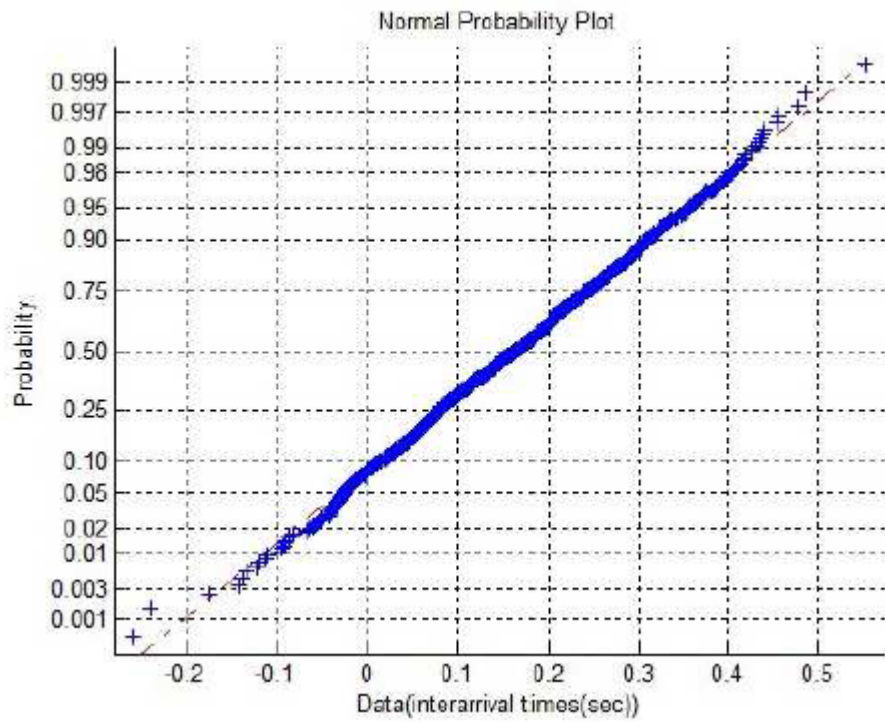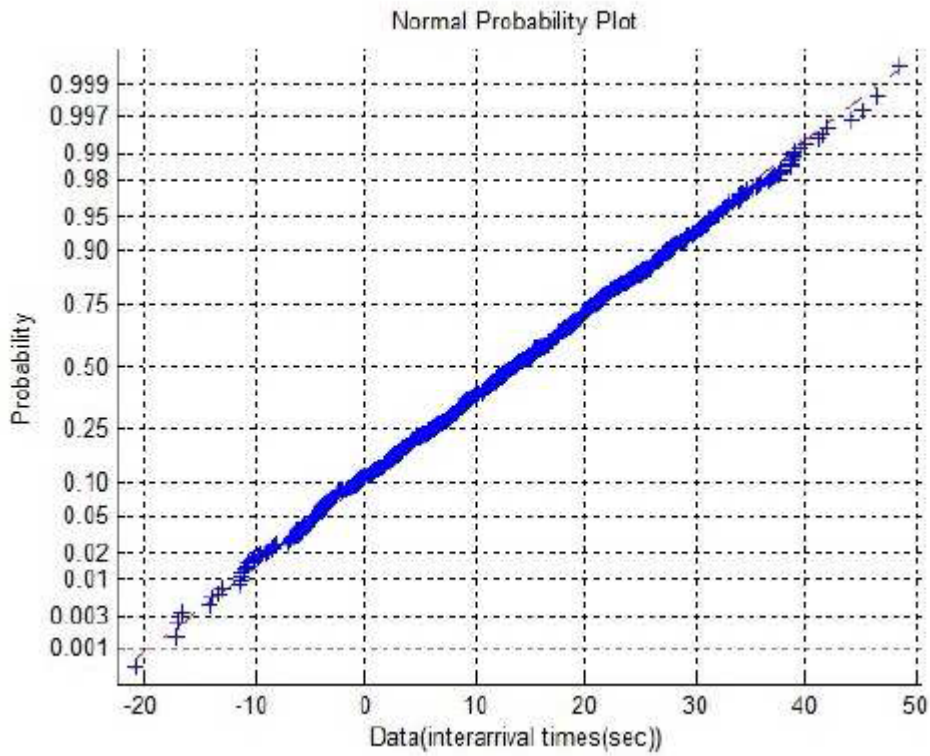

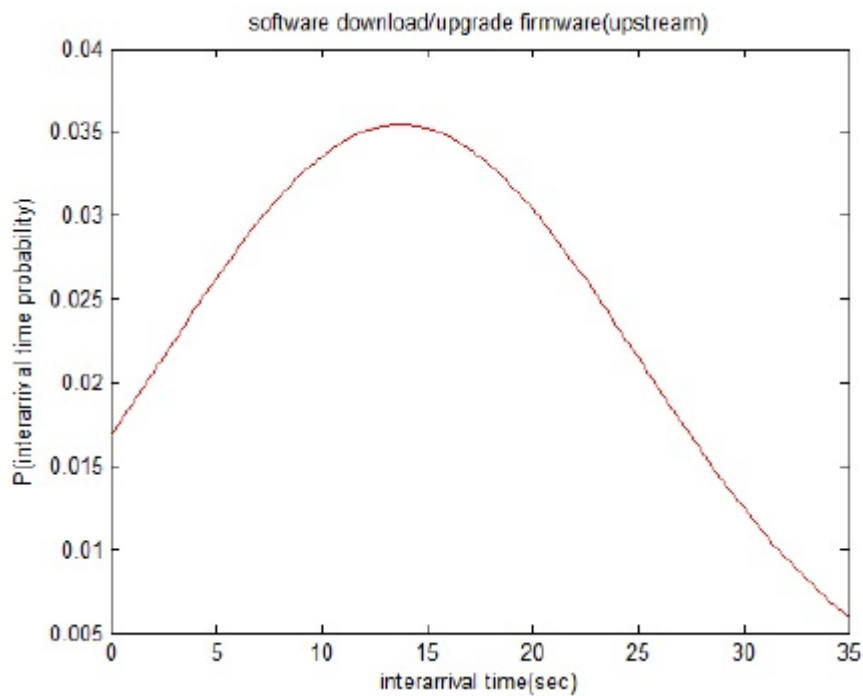*(a) Normal Probability plot*
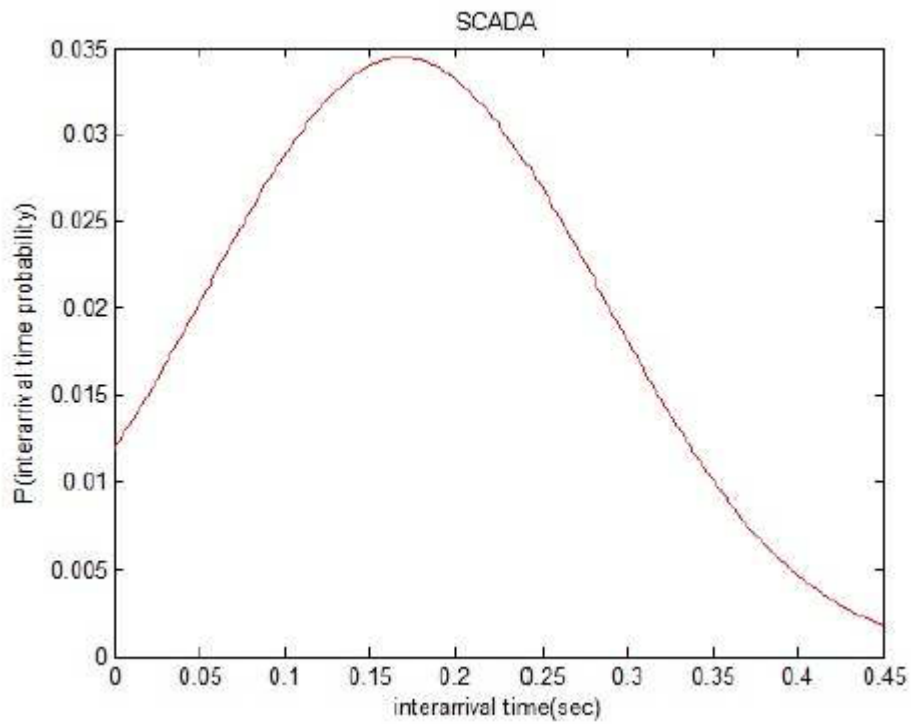
(b) PLOT

Figure 2.7: *SCADA*

$$P_{\text{Upstream software download}} = \frac{1}{11.25 \cdot \sqrt{2\pi}} \cdot \exp\left(-\frac{(x-13.75)^2}{2 \cdot 11.25^2}\right) \qquad (2.9)$$
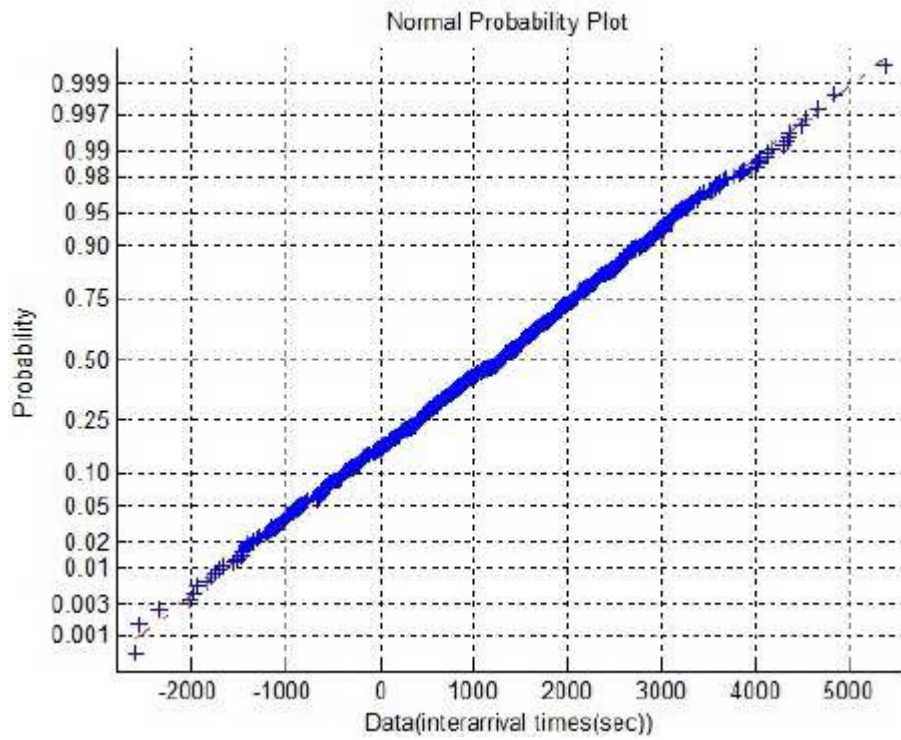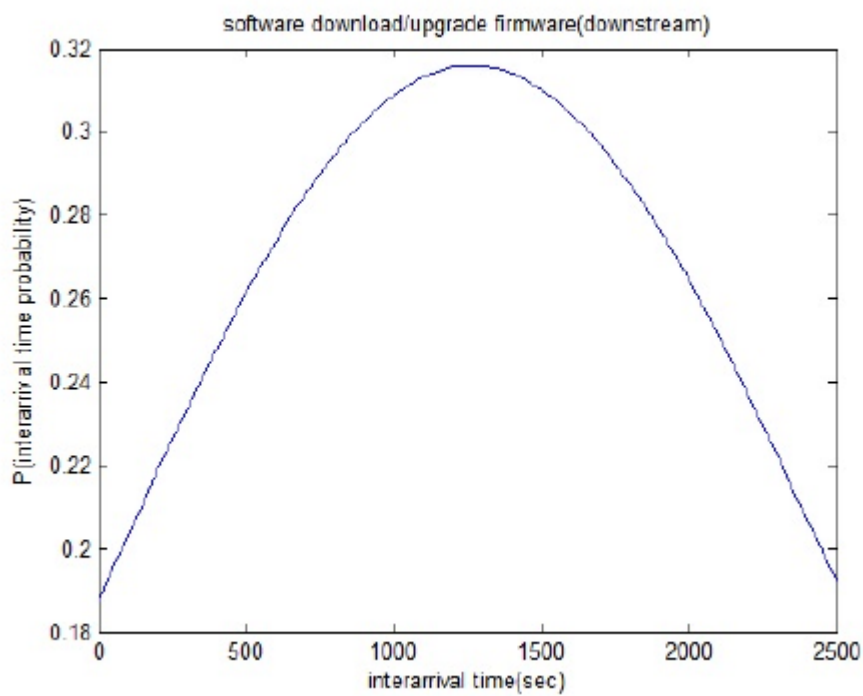

(a) Normal Probability plot

(b) *PLOT*

Figure 2.8: *Upstream Software download/upgrade firmware*

$$P_{\text{Downstream software download}} = \frac{1}{1237.5 \cdot \sqrt{2\pi}} \cdot \exp\left(-\frac{(x-1262.5)^2}{2 \cdot 1237.5^2}\right) \qquad (2.10)$$
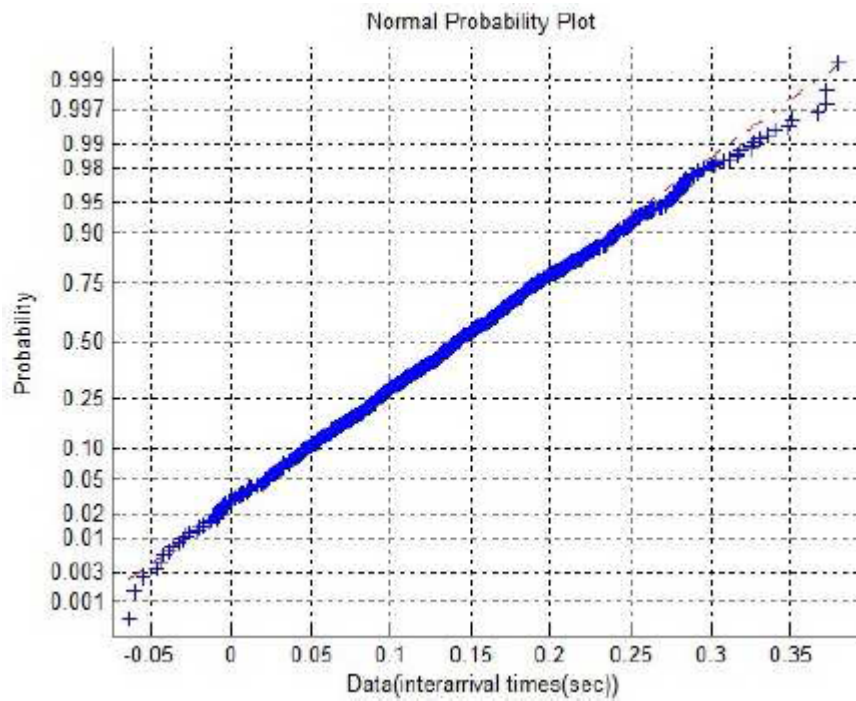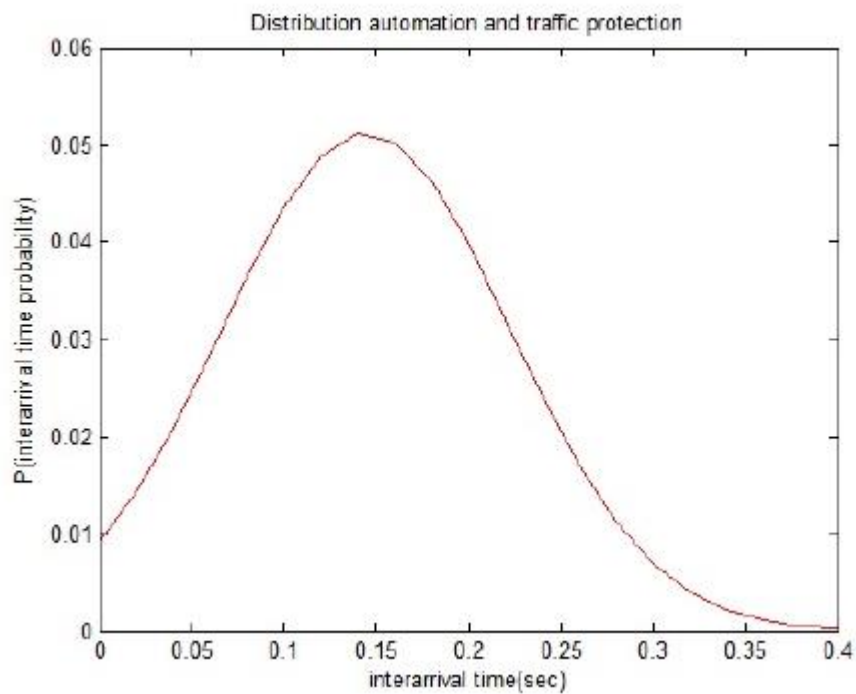

(a)Normal Probability plot

(b) *PLOT*

Figure 2.9: *Downstream Software download/upgrade firmware*

$$P_{\text{Distribution Automaion}} = \frac{1}{0.077777778 \cdot \sqrt{2\pi}} \cdot \exp\left(-\frac{(x - 0.14444444)^2}{2 \cdot 0.077777778^2}\right) \quad (2.11)$$
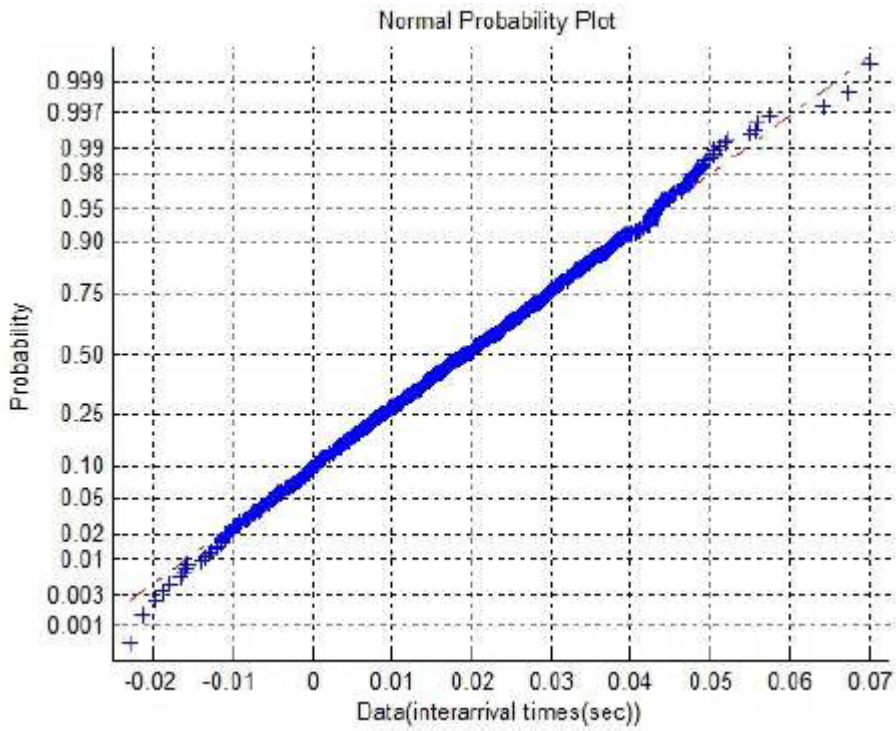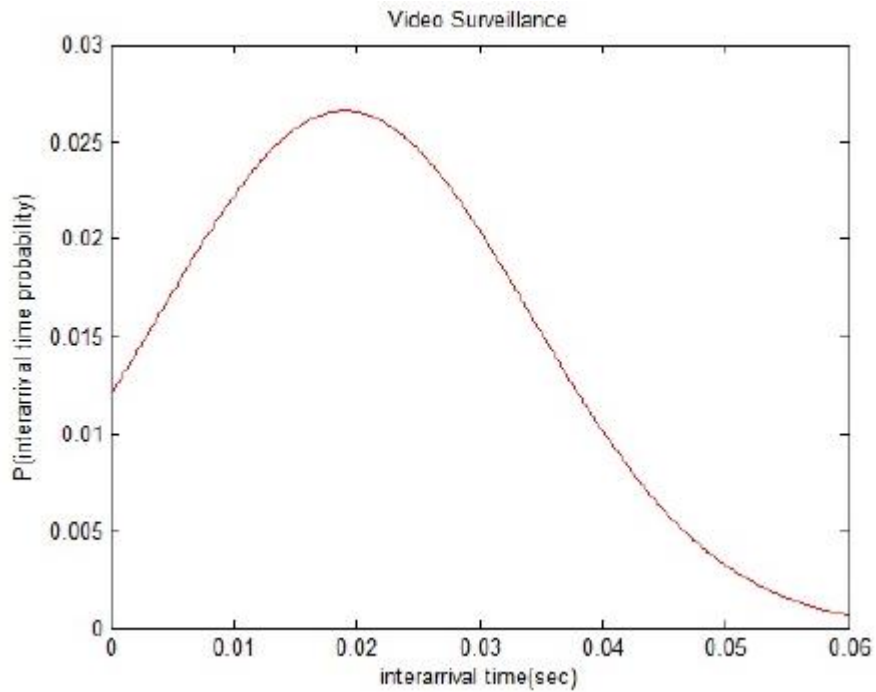

(a)*Normal Probability plot*

(b) *PLOT*

Figure 2.10: *Distribution Automation*

$$P_{\text{Video Surveillance}} = \frac{1}{0.015066667 \cdot \sqrt{2\pi}} \cdot \exp\left(-\frac{(x-0.019066667)^2}{2 \cdot 0.015066667^2}\right) \quad (2.12)$$
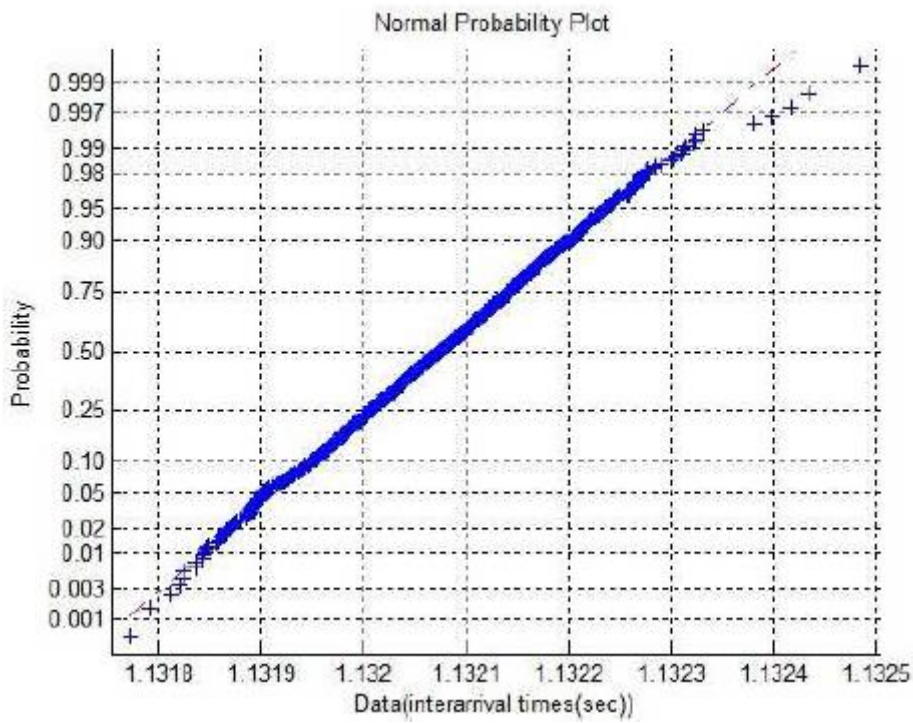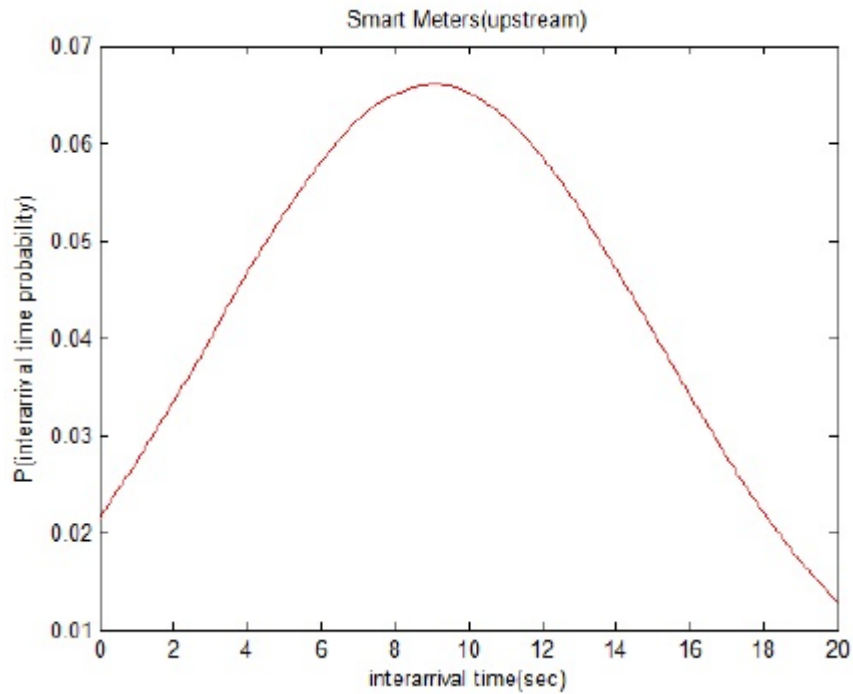

(a)*Normal Probability plot*

(c) PLOT

Figure 2.11: *Video Surveillance*

$$P_{\text{Smart Meters upstream}} = \frac{1}{0.0001 \cdot \sqrt{2\pi}} \cdot \exp\left(-\frac{(x-1.132075472)^2}{2 \cdot 0.0001^2}\right) \quad (2.13)$$
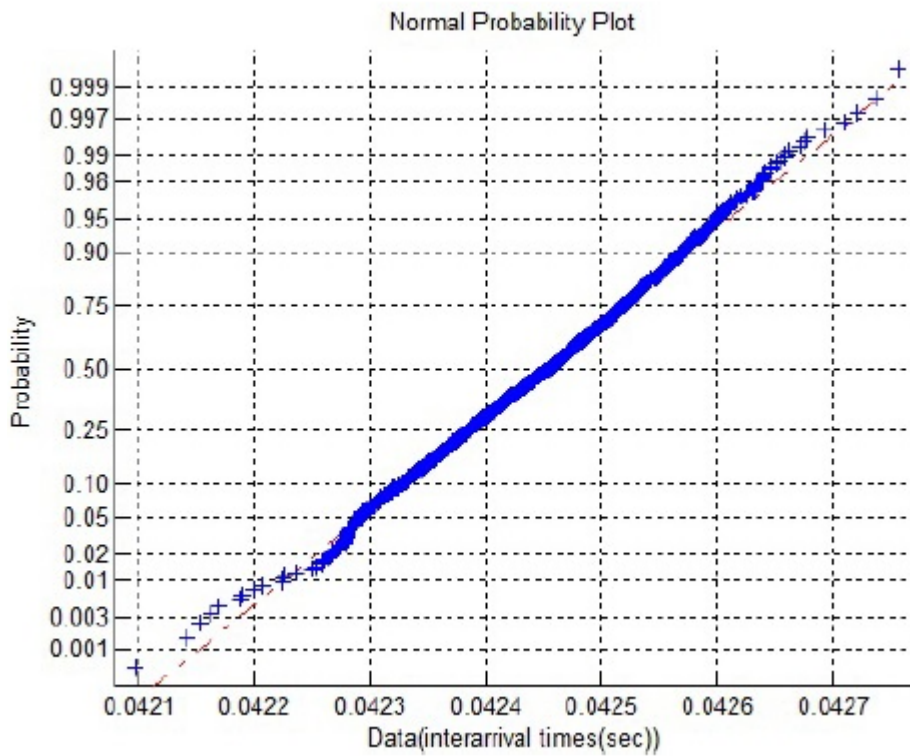

(a) Normal Probability plot

(b) PLOT

<u>Figure 2.12:</u> *Upstream smart metering*

$$P_{\text{Smart Meters downstream}} = \frac{1}{0.0001 \cdot \sqrt{2\pi}} \cdot \exp\left(-\frac{(x-0.04245283)^2}{2 \cdot 0.0001^2}\right) \quad (2.14)$$

(a) Normal Probability plot

(b) PLOT

Figure 2.13: *Downstream smart metering*

$$P_{\text{On demand}-\text{reading}} = \frac{1}{0.016 \cdot \sqrt{2\pi}} \cdot \exp\left(-\frac{(x-0.024)^2}{2 \cdot 0.016^2}\right) \quad (2.15)$$

(a) Normal Probability plot

(b) PLOT

Figure 2.14: *Upstream on demand metering*

$$P_{\text{On demand−reading\_downstream}} = \frac{1}{0.002 \cdot \sqrt{2\pi}} \cdot \exp\left(-\frac{(x-0.006)^2}{2 \cdot 0.002^2}\right) \quad (2.16)$$
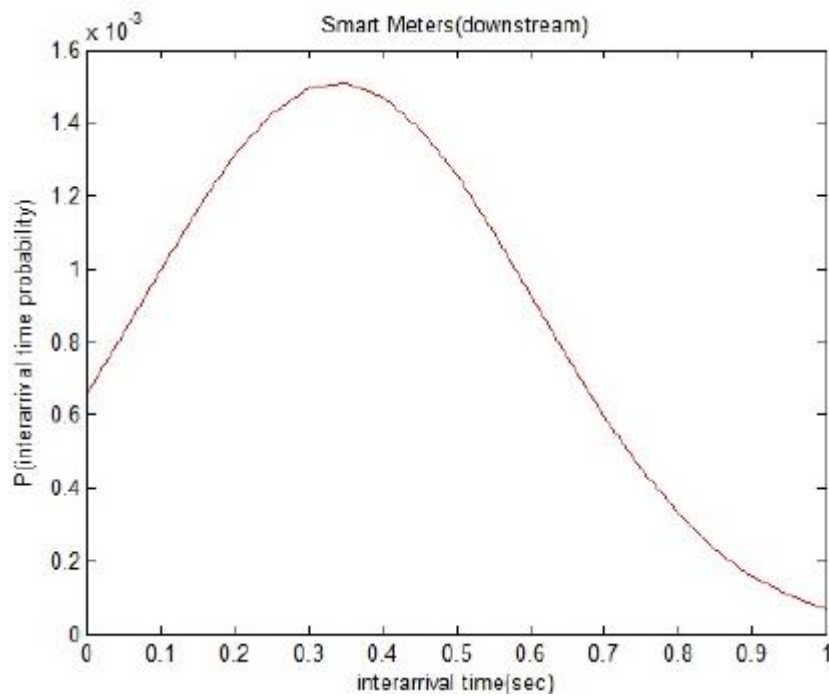

(a) Normal Probability plot
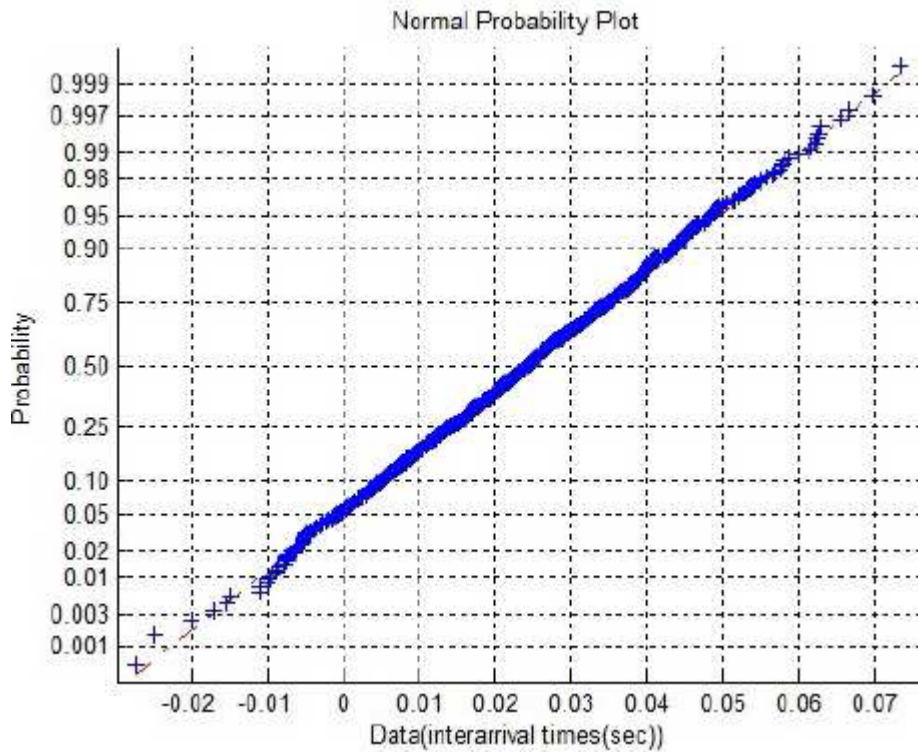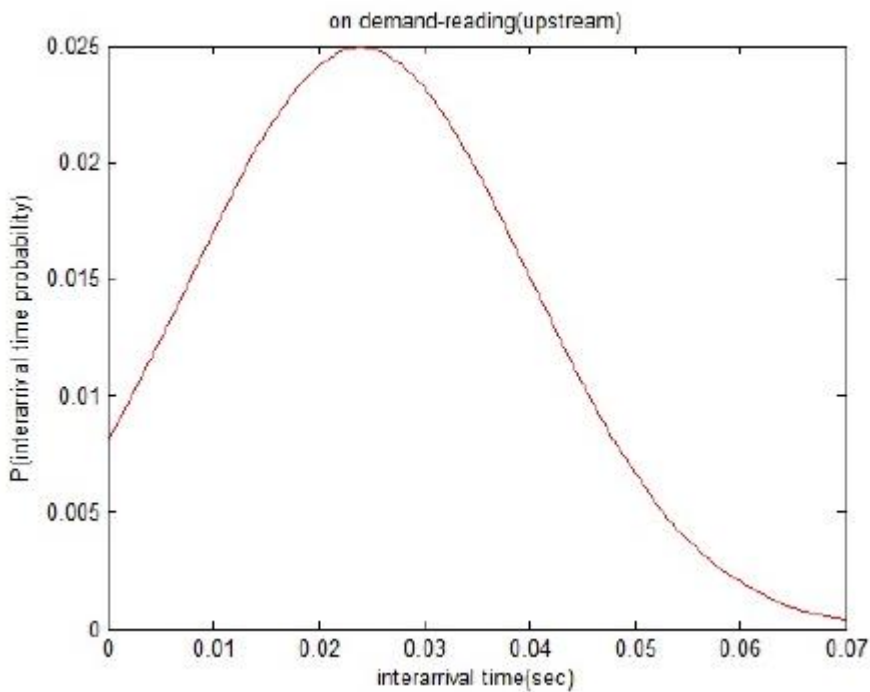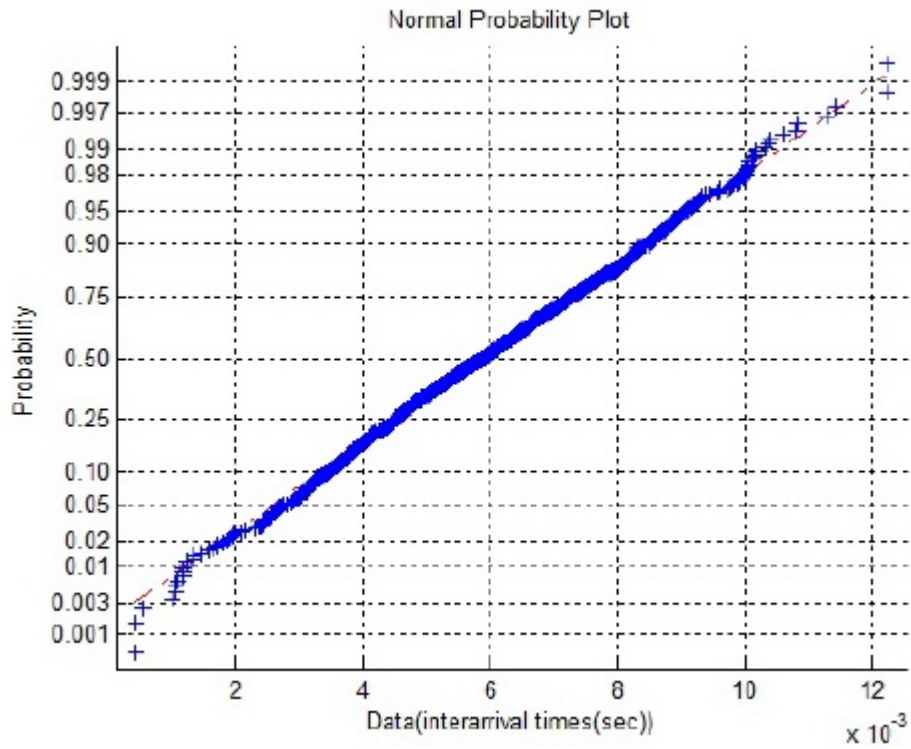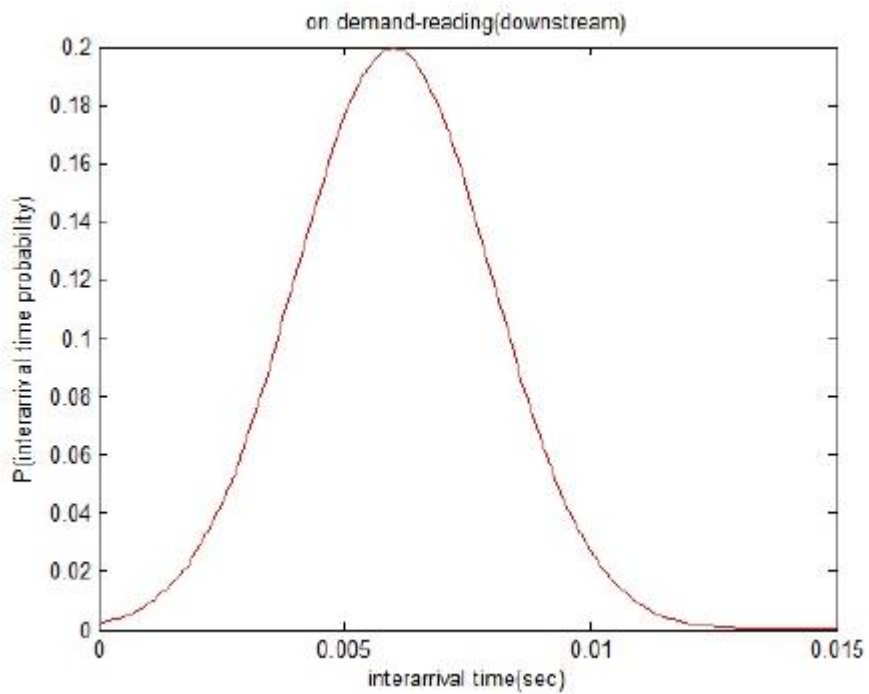

(b) PLOT

Figure 2.15: *Downstream on demand metering*

Concerning the applications in the Table 2.4, for which an expectation of the interarrival time is given, it could be assumed that an exponential distribution with rate λ could describe their traffic, since there are not enough data in the literature in order to be able to determine the exact distribution that their interarrival times follow and compute the parameters of other possible distributions (i.e. normal). Furthermore, in general, assuming exponential distribution is one of the most often simplifying assumptions in making a mathematical model for a real-world phenomenon. The reason for this is that the exponential distribution is not only relatively easy to work with but also is often a good approximation to the actual distribution [30].

A continuous random variable X is said to have an exponential distribution with parameter λ, λ > 0, it has density function:

$$f(x) = \lambda \cdot \exp(\lambda \cdot x), \text{ for x} \geq 0 \qquad (2.17)$$

and is depicted as:
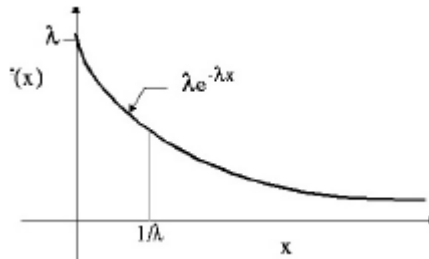
Figure 2.16: *Exponential density function*

In Table 2.4 the expected value of the interarrival time of each of these applications is depicted. The parameter λ of the exponential distribution is [30]:

$$\lambda = \frac{1}{E(T)} \qquad (2.18)$$

where E(T) is the expected value of the interarrival time.

The following Table 2.5contains the parameter λ of these applications:

Table 2.5: *The parameter λ of the Exponential Distribution*

#	**Smart Grid Applications**	**rate λ**
3	Street lighting and traffic control	0.0488
5	Load Management	97.7
6	Alarm Management	18.75
8	Operational telephony	15.6

Thus, distribution functions 2.19-2.22 describe the traffic produced by each application of Table 2.5. Below each expression of distribution function there is a histogram

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of 10000 observations that were randomly sampled from each distribution. The 'values' in the follow plots are referred to interarrival times.

$$f(x) = 0.0488 \cdot \exp(0.0488 \cdot x) \qquad\qquad (2.19)$$

Figure 2.17: *Street lighting and Traffic Control*

$$f(x) = 97.7 \cdot \exp(97.7 \cdot x) \qquad\qquad (2.20)$$

Figure 2.18: *Load Management*

$$f(x) = 18.75 \cdot \exp(18.75 \quad \cdot x) \tag{2.21}$$

Figure 2.19: *Alarm Management*

$$f(x) = 15.625 \cdot \exp(15.625 \quad \cdot x) \tag{2.22}$$
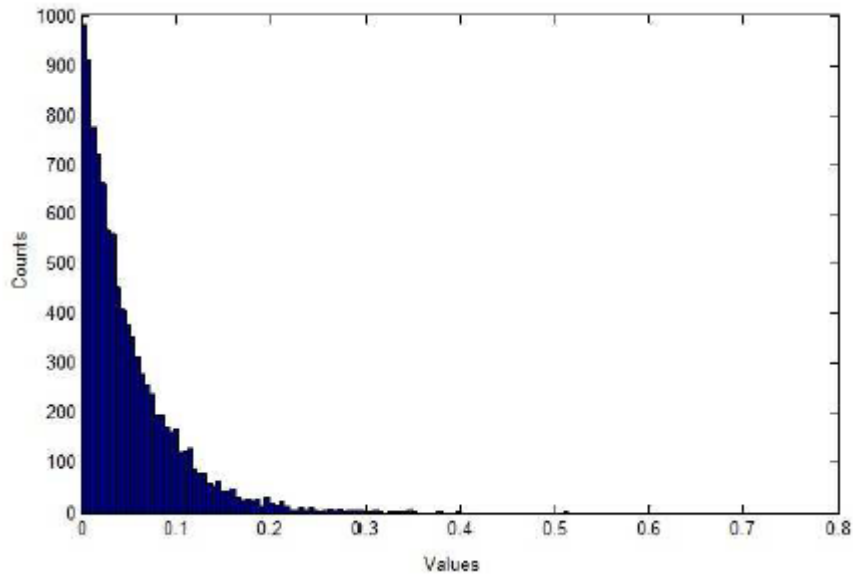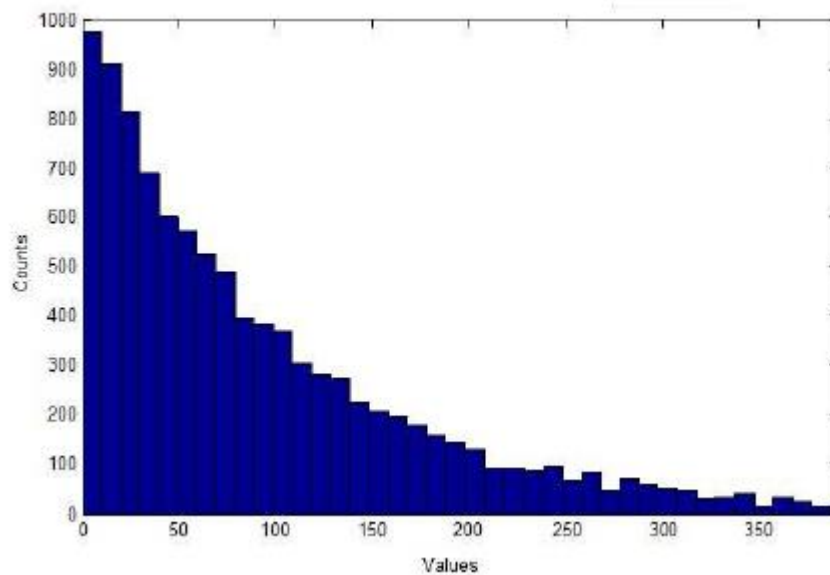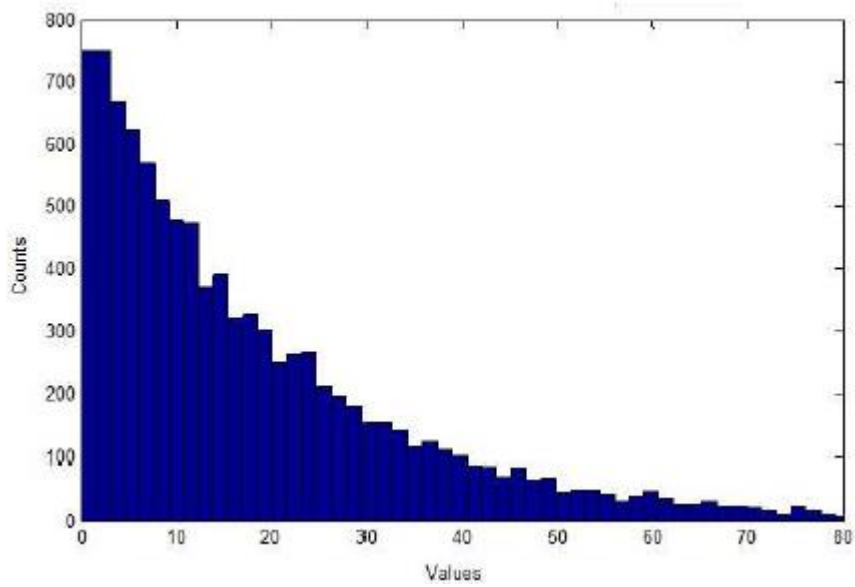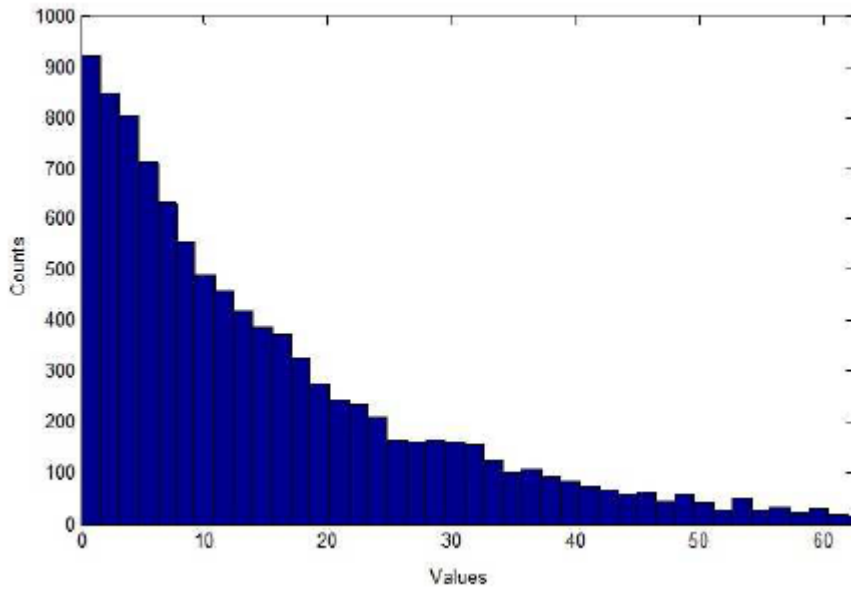

Figure 2.20: *Operational Telephony*

3. Final Traffic Model

3.1. Derivation of the Final Traffic Model as a superposition of all found Application Models

In this chapter, using the formal mathematical models for the traffic produced by each application that have been derived in the previous section, the final traffic model for the traffic produced by all of the applications working simultaneously during a long period of time (for example if t is the time interval that all the applications produce traffic, it is: -∞<t< ∞ is derived. Namely, the final model is a superposition of all found application models.

At first, an analytical expression of the aggregate traffic will be found, while afterwards the final model is described through Matlab.

3.1.1. Analytical expression of the aggregate traffic produced of all the Applications

In the previous chapter, in section Derivation of formal mathematical model for the traffic produced by each application, the formal mathematical models for the traffic of each application have been derived and they are the equations 2.8-2.16 and 2.19-2.22.

A first thought of finding the final model was the use of mixture distribution, but as it is shown in Appendix A this is not an appropriate solution for this case.

In order to find an analytical expression for the final model, all the found application distributions will be approximated by Poisson ones.

At first, the distributions 2.8-2.16 which are normal are approximated by exponential ones. The μ of each normal distribution is its mean value. Thus, according to equation 2.18 and to [33], [34], [35]: $\lambda \cong \frac{1}{\mu}$.

According to [35] there is a relation between the Poisson and the exponential distribution:

$$Poisson_{x=0, \mu=\lambda \cdot t} = \lambda \cdot \exp(\lambda \cdot t) \qquad (3.1)$$

where

$$Poisson = \frac{e^{-\lambda} \cdot \lambda^x}{x!} \qquad (3.2)$$

In the following Table 3.1 the parameter λ of the Poisson distribution of each found applications is included:

Table 3.1: *The parameter λ of the Poisson distribution*

#	Smart Grid Applications	λ of the Poisson distribution
1	SCADA	5.92105
2	Software download/upgrade firmware	
	upstream	0.07272
	downstream	0.00079
3	Street lighting and traffic control	0.0488
4	Distribution automation and traffic protection	6.923]
5	Load Management	97.1
6	Alarm Management	18.75
7	Video Surveillance	52.447
8	Operational telephony	15.6
9	Smart Meters	
	upstream	0.88333
	downstream	23.555
10	On demand-reading	
	upstream	41.7
	downstream	166.67

In general [36]:

Let N_1 (t),...,N_k (t) Poisson processes with parameters λ_1,...,λ_k. Then, the merging superposition of these Poisson processes is a new Poisson Process with rate:

$$\lambda = \sum_{i=1}^{k} \lambda_i \qquad (3.3)$$

If, for example, there are two Poisson processes with parameters λ_1 and λ_2, then their superposition is a Poisson process with rate $\lambda_1 + \lambda_2$ as it is showed in figure 3.1:
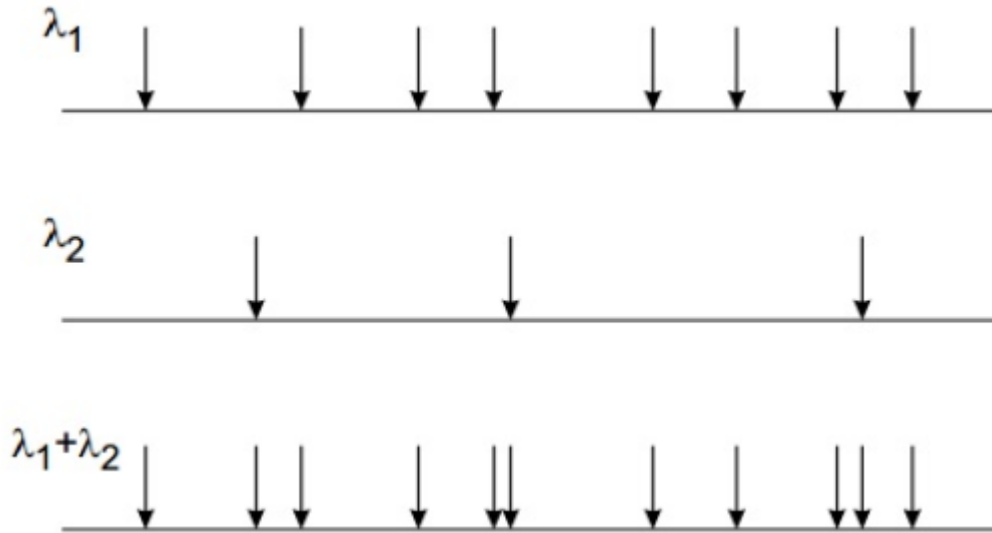
Figure 3.1: *Superposition of two Poisson Processes*

In our case, the final model that is a superposition of the Poisson Processes describing the traffic of each application is a Poisson process with parameter λ :

$$\lambda = \sum_{i=1}^{13} \lambda_i = 430 \qquad (3.4)$$

where λ_i is a poisson parameter from the Table 3.1.

Thus, the analytical final model for the aggregate traffic is:

$$Poisson = \frac{e^{-430} \cdot \lambda 430^x}{x!} \qquad (3.5)$$

A poisson distribution, in general, is a discrete probability distribution that expresses the probability of a given number of events occurring in a fixed interval of time and/or space if these events occur with a known average rate and independently of the time since the last event [36]. Thus, Equation 3.5 gives the probability of a given number of packets arrivals occurring in a time interval-∞<t< ∞). According to \ref{3.5} and [36] the expected value of the interarrival time 'when all of the applications are working' is E[T=$\frac{1}{430}$=0.002325sec

3.1.2.   Model of the aggregate traffic using Matlab

Now, the final traffic model is described by the code in Matlab and from this the expected value of the interarrival time 'when all of the applications are working' is derived.

Using the formal mathematical models for the traffic produced by each application that are described in the equations 2.8-2.16 and 2.19-2.22, random numbers that express random interarrival times for each application are produced. The random interarrival time produced by an application distribution is summarized with its previous. In this way, for each application, we have the times when packets arrive. Afterwards, these times are superposed in a common time axis and sorted in ascending order. Here, it is noticeable that the applications with smaller interarrival times are repeated as many times as necessary in order to 'keep up with' the applications with bigger interarrival times. Thus, having in a common axis the times when a packet arrival occurs by any application the interarrival times can be calculated as well as the expectation value of the interarrival time.

The expectation value of the interarrival time in the final model with Matlab is computed: E[T]=0.0031sec.

It is noticeable that the expected value of the interarrival time derived from the analytical model and the expectation value of the interarrival time were in the same order of magnitude. This fact means that the analytical approximation is good enough, since its result is more less the same with the result of Matlab which is accurate.

4. Throughput Calculation

4.1. **System performance under Greedy Traffic Conditions**

At the Chair of Telecommunications of Technical University of Dresden has already been developed an analytical model for the Medium Access Control (MAC) layer of 'the Narrowband Power Line Communications (NB-PLC) system intended to be used for Smart Grid applications system' [37].

In this section, the calculation of the throughput of the system, as it is described in [37], is briefly presented.

According to [37], the point to point throughput at the MAC layer of the communication network can be described as:

$$S = \frac{\bar{U}}{\bar{B}} \tag{4.1}$$

where:

$$\bar{U} = T_p \cdot P_s \quad \text{the average transmission time within one frame} \tag{4.2}$$

$$\bar{B} = \tau + I + \bar{Y} + T_p \quad \text{the average frame duration} \tag{4.3}$$

T_p: the packet transmission time

P_s: the probability of successful transmission

τ: the propagation delay

I: the constant frame overhead

$\bar{Y}$: the average winner backoff time

After deriving the probability of successful transmission as well as the average winner backoff time and considering as constant the packet transmission time, the propagation delay and the constant frame overhead, the authors in [37] derive the final formula for the throughput, which is the following:

$$S = \frac{T_p \cdot \left(1 - \left(\sum_{i-1}^{CW-i}\left(\frac{1}{CW^N} \cdot \sum_{j=2}^{N}\left(\binom{N}{j} \cdot (CW-j)^{N-j} \right) + \frac{1}{CW^N} \right) \right)}{\tau + I + \sum_{i=1}^{CW} y_i \cdot \left[(1 - \frac{y_i-1}{CW})^N - (1 - \frac{y_i}{CW})^N \right] + T_p} \tag{4.4}$$

So it became possible to analyze the system performance under greedy traffic conditions.

4.2. System performance under Realistic Traffic Conditions

From the system performance analysis in [37] derives equation 4.4 that calculates the point to point throughput of the system under greedy traffic conditions.

In a system under greedy traffic conditions, each "greedy" source has always data to transmit and is never in idle state. The sender side queue is never congested, since a new packet is generated only when the transmission of the previous packet is completed. The throughput of a system calculated under greedy traffic conditions is the maximum of the network [38].

However more detailed analysis under realistic traffic is required. Namely, in this case it is not sure that each source in the network has always a packet to transmit.

So, under realistic traffic, there is a time interval between the arrivals of two sequential data-packets. This interarrival time has to be included in the calculation of the throughput of the system.

The throughout is again described by the equation 4.1. The difference here is in the denominator 4.3. I in 4.3 was the constant frame overhead that summarized the portions of the transmission frame like guard intervals and acknowledgement field that are constant and do not change for the specific system configuration. Now I is replaced by I′ that includes the expected value of the interarrival time. Namely,

$$I'' = I + E[T] \qquad (4.5)$$

As it is obvious in the Figure 2.5, the interarrival time includes the transmission time. So, the term T_P has to be removed from the denominator, since it is included in the term E[T].

Thus, throughput can now be described as:

$$S = \frac{T_p \cdot P_s}{\tau + I + E[T] + \bar{Y}} \qquad (4.6)$$

and Equation 4.4 becomes:

$$S = \frac{T_p \cdot \left(\ 1 - \left(\ \sum_{i-1}^{CW-i}\left(\frac{1}{CW^N} \cdot \sum_{j=2}^{N}\left(\binom{N}{j} \cdot (CW-j)^{N-j}\right) + \frac{1}{CW^N}\right)\ \right)\right)}{\tau + I + E[T] + \sum_{i=1}^{CW} y_i \cdot \left[(1 - \frac{y_i - 1}{CW})^N - (1 - \frac{y_i}{CW})^N\right]} \qquad (4.7)$$

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Equation 4.7 refers to the aggregate throughput of the system if in the system more than one application coexists. The $E[T]$ is the mean interarrival time between the packets and is depends of the interarrival times of each application.

In general, the interarrival time of packets entering the network varies and is not the same for all the packets.

5. Results

5.1.System performance under Realistic Traffic Conditions

In this section the performance of the system under realistic traffic in terms of aggregate throughput is studied, by varying the different parameters of the traffic and the system model. Equation 4.7 is used for the calculation of the throughput for different scenarios, taking into account different subsets of the working applications.

Some comments regarding the acquisition of the results:

- the parameters τ and I that exist in Equation 4.7, as well as the transmission speed, are characteristics of the specific channel used and therefore are considered to be constant. Specifically in this case: $\tau = 6.667*10^{-9}$sec, I $=1.827*10^{-2}$sec, B $= 56$kbps (these values are the same with the respective values in the model for throughput calculation under greedy conditions in [37]).

- As it is explained in *System performance under Realistic Traffic Conditions* E[T] is the expected value of the interarrival time of packets. It can be derived either from the analytical model, as described in *Analytical expression of the aggregate traffic produced of all the Applications*, or by using Matlab. In section *Final Traffic Model*, the expected value of the interarrival time has been calculated in both ways analytical and via Matlab simulations- in the case that all the applications are working. The results were in the same order of magnitude. In this Section, the result of the Matlab simulation will be used for the calculation of E[T] for each scenario.

- the capacity of the channel is specific, B $= 56$kbps, as it has already referred. So the sum of the needed bandwidths of the applications that coexist in the system should be ≤ 56kbps. The scenarios considered for throughput calculation are based on combinations of working applications that qualify this restriction.

- the applications will not have the same packetsize with each other but each one will have different packetsize from the others according to the data provided by literature and are presented in Table 2.1.

- in Equation 4.7 the term T_p is the transmission time and depends on the packet size. However, packets from different applications have different lengths, as it has already referred and therefore different transmission time from each other. For simplicity reasons a mean value of the transmission times of different applications sending packets in each case will be considered as T_p in Equation 4.7 (namely it will be $\overline{Tp}$).

Next, an enumeration of the scenarios used will be presented. Afterwards, a plot of throughput versus contention window (CW) for different number of nodes (depending on

the scenario) is presented and the optimal contention window for each case is found. Specifically, plots for 8, 16 and 32 nodes will be presented, because these numbers of nodes are realistic enough for the concerned scenarios. The performance of each different case is studied.

I. **SCADA** and **Smart metering** are of the most important and the most common applications in Smart Grid, especially for the directly interaction with the end-user. This is why a scenario with only the two of them working is now considered.

The restriction for the bandwidth is fulfilled, since the needed bandwidth for the SCADA application is 9.6kbps (maximum one) and for Upstream Smart metering and Downstream Smart metering 5.3kbps each, as it is shown in Table 2.1. Observing the Table 2.1, a typical packet of SCADA application is 512 bits, while a mean packet size for Upstream Smart metering is 48000 bits and for Downstream Smart metering is 1800 bits. The interarrival times of these applications with the specific bandwidth and packet size values are shown in Table 2.1.

The expected value of the interarrival time is found using Matlab simulation to be $E[T]=0.1676$ sec.

In Figure 5.1, the throughput versus contention window is plotted for different number of nodes:
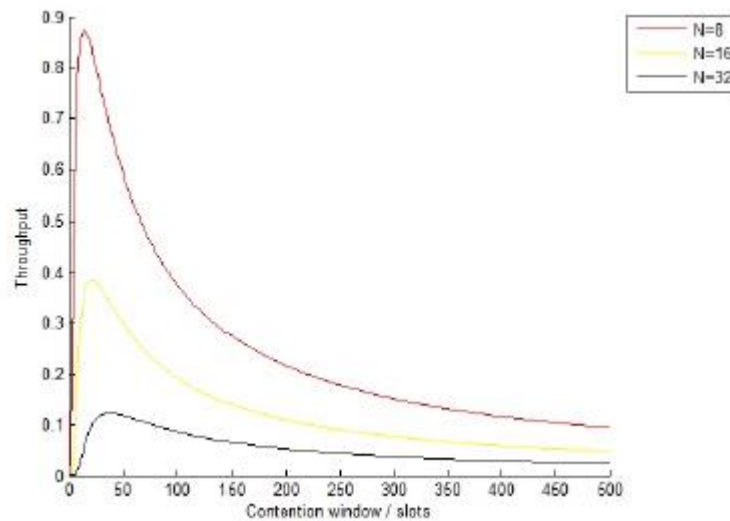

Figure 5.1: *Throughput vs contention window/slots for scenario 2 and for different number of nodes*

The optimal contention window for different number of nodes can be extracted and is shown in Table 5.1 :

Table 5.1: *The optimal Contention Window for different number of nodes for Scenario 1*

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Number of nodes (N)	Throughput	Optimal Contention Window
8	0.9146	19
16	0.5195	25
32	0.1432	41

II. In scenario 2 **SCADA**, **Alarm Management, Distribution Automation, Operational Telephony}** and **Smart metering** are included. In case that a lot of perturbations occur and the grid has to be protected from them, fault detection and protection and Alarm management are of major importance. Smart metring and SCADA continue to be important too.

The restriction for the bandwidth is fulfilled, since the needed bandwidth for the SCADA application is 9.6kbps (maximum one), for Alarm Management is also 9.6kbps, for Distribution Automation is 18kbps, for Operational Telephony is 8kbps and for Upstream Smart metering and Downstream Smart metering 5.3kbps each, as it is shown in Table 2.1. Observing the Table 2.1, a typical packet of SCADA, Alarm Management and Operational Telephony application is 512 bits, while a mean packet size for DA is 2600bits, for Upstream Smart metering is 48000 bits and for Downstream Smart metering is 1800 bits. The interarrival times of these applications with the specific bandwidth and packet size values are shown in Table 2.2.

The expected value of the interarrival time is found using Matlab simulation to be E[T] =0.0556 sec.

In Figure 5.2, the throughput versus contention window is plotted for different number of nodes:
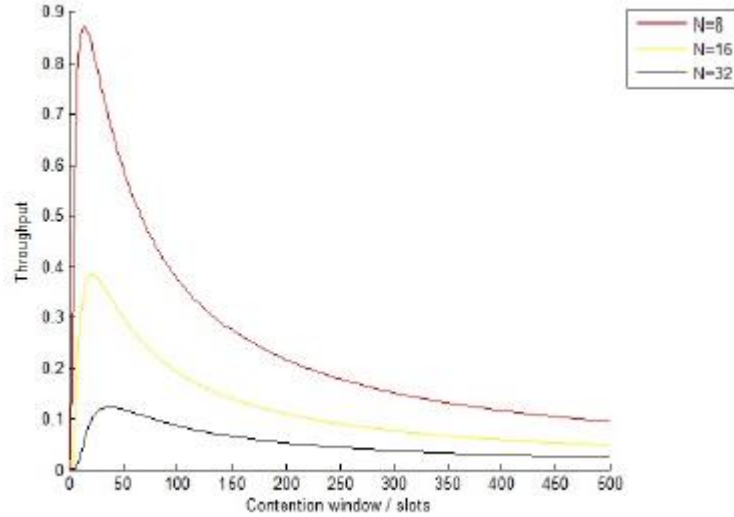
Figure 5.2: *Throughput vs contention window/slots for scenario 2 and for different number of nodes*

The optimal contention window for different number of nodes can be extracted and is shown in Table 5.2:

Table 5.2: *The optimal Contention Window for different number of nodes for Scenario 2*

Number of nodes (N)	Throughput	Optimal Contention Window
8	0.8737	14
16	0.3854	22
32	0.1229	38

III. **SCADA, Video Surveillance** and **Smart metering** are working in scenario 3. The security is very important in this case, having had real-time video feeds from each substation as well as video recording and archiving.

The restriction for the bandwidth is fulfilled, since the needed bandwidth for the SCADA application is 9.6kbps (maximum one) and for Upstream Smart metering and Downstream Smart metering 5.3kbps each, as it is shown in Table 2.1.35.8kbps Bandwidth is allocated for Video Surveillance in order the channel capacity restriction not to be violated. Observing the Table 2.1, a typical packet of SCADA and Video Surveillance application is 512 bits, while a mean packet size for Upstream Smart metering is 48000 bits and for Downstream Smart metering is 1800 bits. The interarrival times of these applications with the specific bandwidth and packet size values are shown in Table 2.2.

The expected value of the interarrival time is found using Matlab simulation to be E[T]=0.0369 sec.

In Figure 5.3, the throughput versus contention window is plotted for different number of nodes:
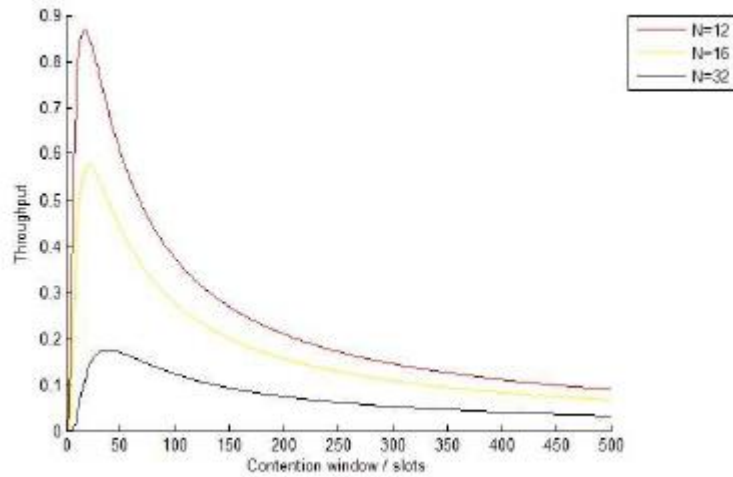
Figure 5.3: *Throughput vs contention window/slots for scenario 3 and for different number of nodes*

The optimal contention window for different number of nodes can be extracted and is shown in Table 5.3:

Table 5.3: *The optimal Contention Window for different number of nodes for Scenario 3*

Number of nodes (N)	Throughput	Optimal Contention Window
8	0.8676	17
16	0.5746	21
32	0.1762	37

IV. **SCADA, Street lighting, Video Surveillance Distribution Automation** and **Smart metering** are working in scenario 4.

The restriction for the bandwidth is fulfilled, since the needed bandwidth for the SCADA application is 9.6kbps (maximum one),for Street lighting is 0.025kbps,for DA is 18kbps and for Upstream Smart metering and Downstream Smart metering 5.3kbps each, as it is shown in Table 2.1.17.775kbps Bandwidth is allocated for Video Surveillance in order the channel capacity restriction not to be violated. Observing the Table 2.1, a typical packet of SCADA and Video Surveillance application is 512 bits, while a mean packet size for DA is 2600bits, for Upstream Smart metering is 48000 bits and for Downstream Smart metering is 1800 bits. The interarrival times of these applications with the specific bandwidth and packet size values are shown in Table 2.2.

The expected value of the interarrival time is found using Matlab simulation to be E[T] =0.0369 sec.

In Figure 5.4, the throughput versus contention window is plotted for different number of nodes:

Figure 5.4: *Throughput vs. contention window/slots for scenario 4 and for different number of nodes*

The optimal contention window for different number of nodes can be extracted and is shown in Table 5.4:

Table 5.4: *The optimal Contention Window for different number of nodes for Scenario 3*

Number of nodes (N)	Throughput	Optimal Contention Window
8	0.7646	15
16	0.4701	20
32	0.1307	38

V.   **SCADA** and **Load Management** are working in scenario 5.

The restriction for the bandwidth is fulfilled, since the needed bandwidth for the SCADA application is 6kbps (maximum one) and for Load Management is 50kbps, as it is shown in Table 2.1 .17.775kbps Bandwidth is allocated for Video Surveillance in order the channel capacity restriction not to be violated. Observing the Table 2.1, a typical packet of both SCADA and Load Management application is 512 bits. The interarrival times of these applications with the specific bandwidth and packet size values are shown in Table 2.2.

The expected value of the interarrival time is found using Matlab simulation to be E[T]=0.1526 sec.

In Figure 5.5, the throughput versus contention window is plotted for different number of nodes:
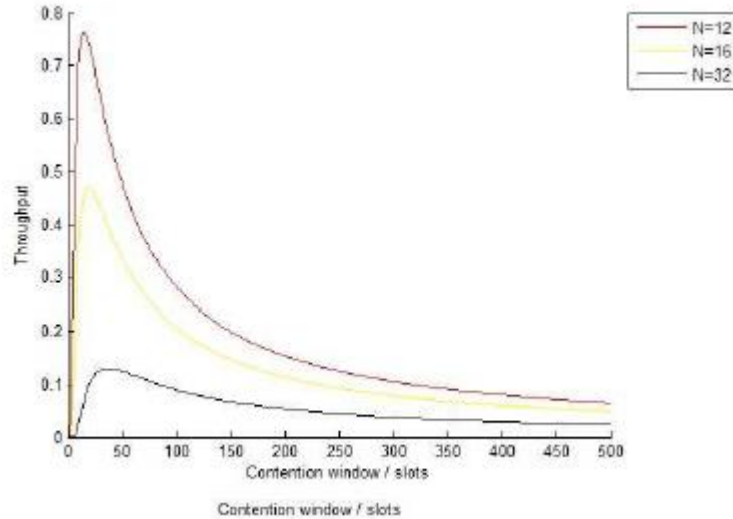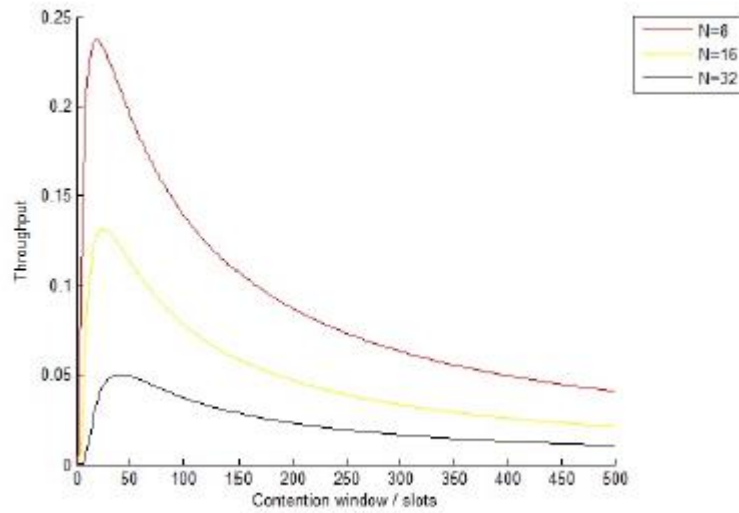
Figure 5.5: *Throughput vs. contention window/slots for scenario 5 and for different number of nodes*

The optimal contention window for different number of nodes can be extracted and is shown in Table 5.5:

Table 5.5: *The optimal Contention Window for different number of nodes for Scenario 3*

Number of nodes (N)	Throughput	Optimal Contention Window
8	0.2369	18
16	0.1315	25
32	0.0503	41

Observing the Figures $5.1 - 5.5$ and the Tables $5.1 - 5.5$, it could be extracted that as the number of nodes in the system increases, the throughput decreases while the optimal value of contention window increases. It would be interesting also to analyze the dependency of the throughput from optimal contention window size for different packet sizes / interarrival times, but it not possible in this study. As it has already referred, each application has different packet length from each other and a corresponding needed bandwidth. Even if applications with same packet length are considered (namely the Street lighting, the load management, the Alarm Management, the Video Surveillance and the Operational Telephony application with packet size 512 bits Table 2.1), it is not possible to calculate the throughput for another value of packet length, because the corresponding needed bandwidth for each application will be different for different packet length and therefore unknown.

5.2. System performance under Realistic Traffic Conditions for a different channel

If another channel with bigger bandwidth is considered, many other scenarios of working applications could be assumed. In this section the bandwidth of the channel is not 56kbps but it assumed to be 400kbps in order all the referred applications to coexist in the system. Other scenarios are possible too.

Some comments regarding the acquisition of the results:

- The propagation delay does not depend on channel bandwidth as it is also proved by its definition [40]:

$$\tau = \frac{l \cdot \sqrt{\varepsilon_r}}{c} \qquad (5.1)$$

where:

l: the length of channel

ε_r: the dielectric constant of the insulation material

c: the speed of light in vacuum

Thus, since the length of the channel and the material do not change: $\tau = 6.667*10^{-9}$ sec.

- the constant frame overhead I is characteristic of the protocol used, so it remains the same too.

- the calculation of the mean interarrival time is done by Matlab simulation, as it has been done in Section *System performance under Realistic Traffic Conditions*.

Next, an enumeration of the scenarios used will be presented. Afterwards, such as in Section *System performance under Realistic Traffic Conditions* a plot of throughput versus contention window (CW) for different number of nodes (depending on the scenario) is presented and the optimal contention window for each case is found. Specifically, plots for 8, 16 and 32 nodes will be presented.

I. at first, it is considered that all the applications are working in the system.
    The expected value of the interarrival time is found using Matlab simulation to be E[T]=0.0037 sec.
    In Figure 5.6, the throughput versus contention window is plotted for different number of nodes:
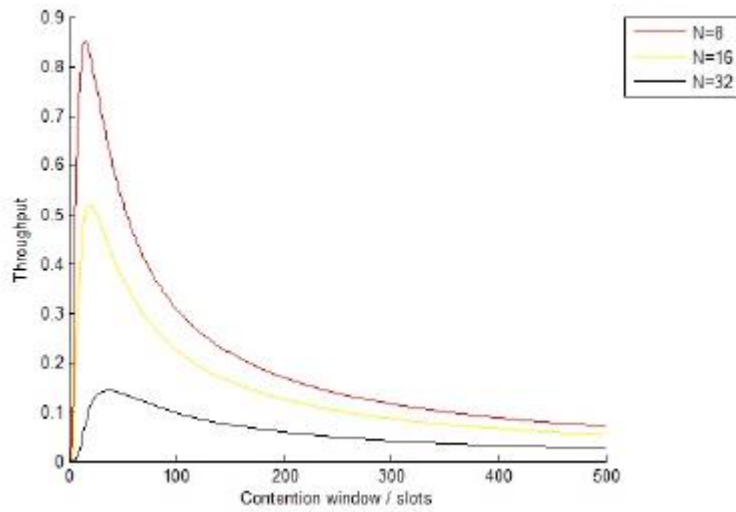
Figure 5.6: *Throughput vs contention window/slots for scenario 1 and for different number of nodes*

The optimal contention window for different number of nodes can be extracted and is shown in Table 5.6:

Table 5.6: *The optimal Contention Window for different number of nodes for Scenario 1*

Number of nodes (N)	Throughput	Optimal Contention Window
8	0.8506	13
16	0.5195	19
32	0.1432	38

II.   According to this scenario, the working applications are: **Load Management, Alarm Management** and **Distribution Automation.** It describes processes to monitor, identify and manage congestion within the local grid supported by DLC+VIT4IP [4].

The expected value of the interarrival time is found using Matlab simulation to be E[T] =0.1760 sec.

In Figure 5.7, the throughput versus contention window is plotted for different number of nodes and when the channel bandwidth is 400kbps:
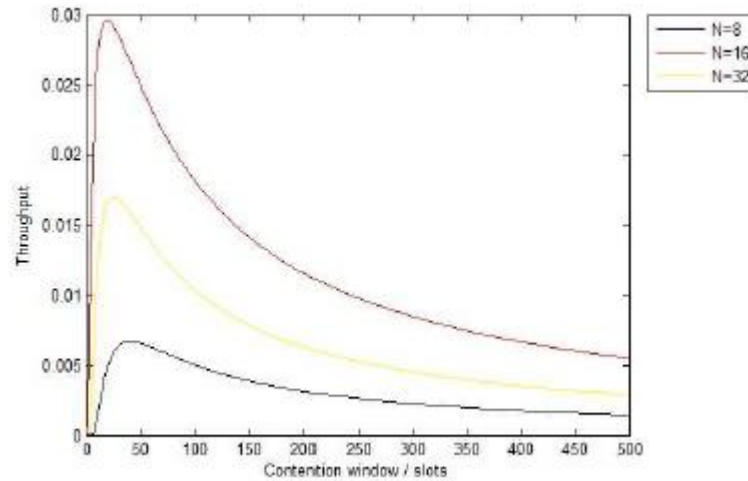
Figure 5.7: *Throughput vs. contention window/slots for scenario 2 for channel bandwidth 400kbps and for different number of nodes*

The throughput will be improved if the used channel wouldn't have much more bandwidth than the working applications need. After the summation of the needed bandwidths of the applications, it is concluded that a channel bandwidth 80kbps would be appropriate in order Load Management, Alarm Management and Distribution Automation coexist in the system.

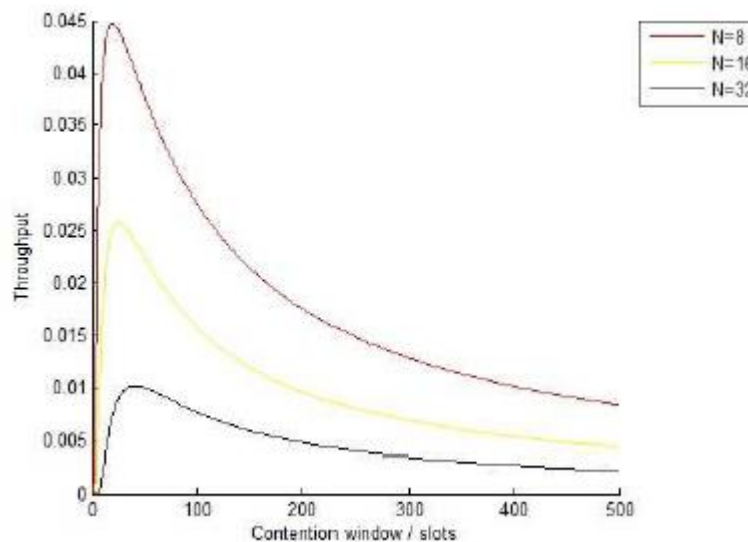In Figure 5.8, the throughput versus contention window is plotted for different number of nodes:

Figure 5.8: *Throughput vs. contention window/slots for scenario 2 for channel bandwidth 80kbps and for different number of nodes*

In the case of the channel of 80kbps bandwidth, the throughput is much improved because there is not a lot of bandwidth that remains unused.

The optimal contention window for different number of nodes can be extracted and is shown in Table 5.7:

Table 5.7: *The optimal Contention Window for different number of nodes for Scenario 2*

Number of nodes (N)	Throughput	Optimal Contention Window
8	0.0447	21
16	0.0256	28
32	0.0101	45

III. **Load management, Video surveillance, Smart metering** are working in scenario 2. The security is very important in this case, having have real-time video feeds from each substation as well as video recording and archiving.

The expected value of the interarrival time is found using Matlab simulation to be E[T] =0.0337 sec.

In Figure 5.9, the throughput versus contention window is plotted for different number of nodes and when the channel bandwidth is 400kbps:
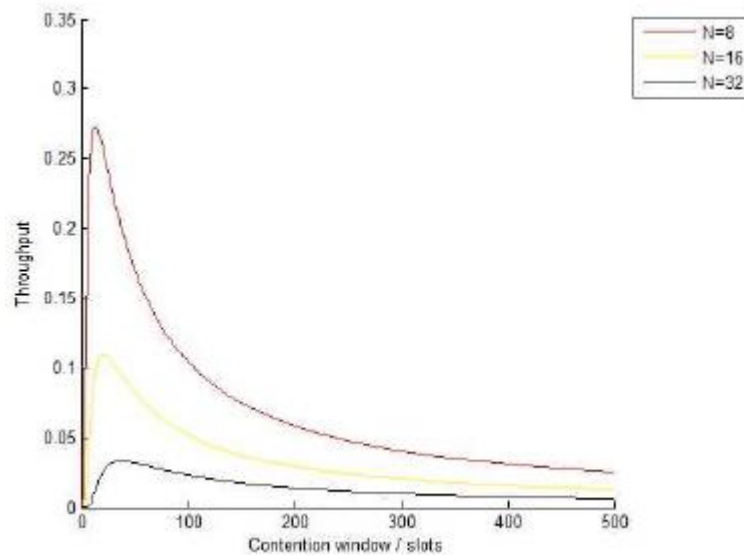

Figure 5.9: *Throughput vs. contention window/slots for scenario 3 for channel bandwidth 400kbps and for different number of nodes*

The throughput will be improved if the used channel wouldn't have much more bandwidth than the working applications need. After the summation of the needed bandwidths of the applications, it is concluded that a channel bandwidth 140kbps would be

appropriate in order Load Management, Video surveillance and Smart metering coexist in the system. With this bandwidth Video can be of high quality.

In Figure 5.10 the throughput versus contention window is plotted for different number of nodes:
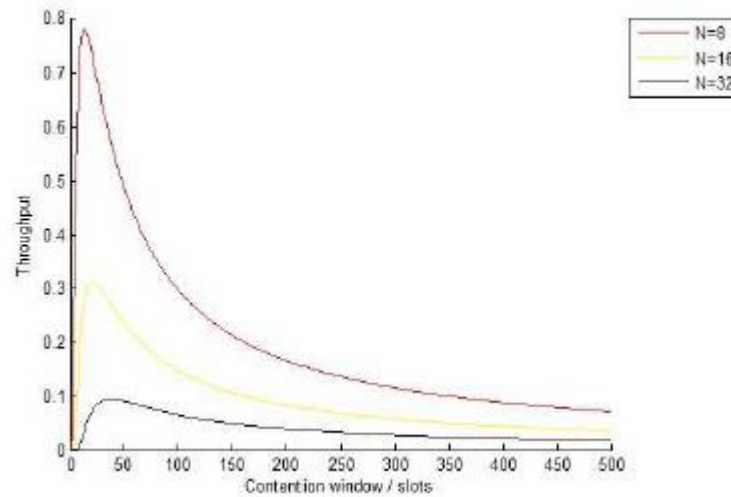

Figure 5.10: *Throughput vs. contention window/slots for scenario 3 for channel bandwidth 140kbps and for different number of nodes*

In the case of the channel of 140kbps bandwidth, the throughput is much improved because there is not a lot of bandwidth that remains unused.

The optimal contention window for different number of nodes can be extracted and is shown in Table 5.8:

Table 5.8: *The optimal Contention Window for different number of nodes for Scenario 3*

Number of nodes (N)	Throughput	Optimal Contention Window
8	0.7791	13
16	0.3125	21
32	0.0943	38

Such as in Section *System performance under Realistic Traffic Conditions*, observing the Figures 5.6 – 5.10 and the Tables 5.6 – 5.10, it is concluded that as the number of nodes in the system increases, the throughput decreases while the optimal value of contention window increases. In this section, it is also shown the dependency of the throughput of the bandwidth of the channel. If the channel bandwidth is much bigger than the needed by the applications bandwidth, the throughput decreases.

6. Conclusions

In this work the performance of a system consisting of Smart Grid applications that could possibly coexist in a future Smart Grid was studied. Ten Smart Grid Applications were proposed to work in this system: SCADA, Software download/upgrade firmware, Street lighting and traffic control, Distribution Automation and traffic protection, Load Management, Alarm Management, Video Surveillance, Operational Telephony, Smart Meters and On demand Meter Reading. Based on the description of each application and data provided by the relevant literature, a mathematical model for the traffic that each application may produce was derived. Specifically, for some applications (SCADA, Software download/upgrade firmware, Distribution Automation, \ Video Surveillance Smart Meters, On demand Meter Reading) normal distributions were chosen to describe their traffic, while the traffic of the remaining applications (Street lighting and traffic control, Load Management Alarm Management, Operational Telephony) was described by exponential ones. Afterwards, the final model that describes the traffic created in the network by all the applications working simultaneously was derived in two ways. At first, the analytical expression 3.5 was proposed to describe the aggregate traffic. The second way was a simulation with Matlab. Namely, the expected value of the interarrival time 'when all of the applications coexist' was derived from a Matlab code. It is remarkable that the expectations of the interarrival time derived from both ways were of the same order of magnitude. Then, the system model available at the chair was modified in order to calculate the throughput in real traffic conditions and the expression derived is the Equation 4.7. Finally, the performance in terms of aggregate throughput was studied, changing the different parameters of the traffic and the system model and taking into consideration different subsets of working applications. In the results, plots of throughput versus contention window (CW) for different number of nodes (depending on the scenario) were presented and the optimal contention window for each case was found. At first it was considered the same channel as in [37] with bandwidth 56kbps. In this case, the scenarios considered for throughput calculation are based on combinations of working applications that qualify the restriction of this channels 'bandwidth. Afterwards, a channel with 400kbps was considered in order all the referred applications could coexist. In this section, other scenarios were also implemented. In both cases, it was observed that as the number of nodes in the system increases, the throughput decreases while the optimal value of contention window increases. In the second Section of the results the dependency of the throughput of the bandwidth to the channel was also shown.

It would be also interesting to analyze the dependency of the throughput from optimal contention window size for different packet sizes / interarrival times, but in the framework of this study, this was not be possible for reasons that have already be explained in Section *System performance under Realistic Traffic Conditions.*

Appendix A

A.1. Mixture Distribution

Given:

- a finite set of probability density functions $p_1(x)...p_n(x)$

- or corresponding cumulative distribution functions $P_1(x)...P_n(x)$

- and weights $w_1...w_n$ such that $w_i \geq 0$ and $\sum w_i = 1$,

the density function of the mixture distribution is:

$$f(x) = \sum_{i=1}^{n} w_i p_i(x) \qquad\qquad (A.1)$$

and its distribution function is:

$$f(x) = \sum_{i=1}^{n} w_i P_i(x) \qquad\qquad (A.2)$$

In our case, it could be assumed that the final model of the aggregate traffic, provoked by all the applications, is a mixture distribution with mixture components the distribution functions of each application and weights $w_1...w_n$ such that $w_i \geq 0$ and $\sum w_i = 1$. Namely, the mixture components are the distribution functions 2.8-2.16 and 2.19-2.22 derived in *Derivation of formal mathematical model for the traffic produced by each application*, which are normal and exponential distributions.

Although mixture distribution seems to be a logical approximation for the derivation of the final traffic model, a random example will show that is inappropriate for our case.

Assuming three random normal distributions with random variable the interarrival times, the desired superposition of the interarrival times of all the distributions is found and compared with their mixture distribution. The desired superposition is found as described in the MATLAB code in *codeA1* and the mixture distribution is calculated with the MATLAB command *gmdistribution.*

In figure A.1 the normal probability plots of both the superposition (S) and the mixture distribution (R) are depicted. The purpose of a normal probability plot is to graphically assess whether the data in X could come from a normal distribution. If the data are normal the plot will be linear [32].The two normplots are different from each other.
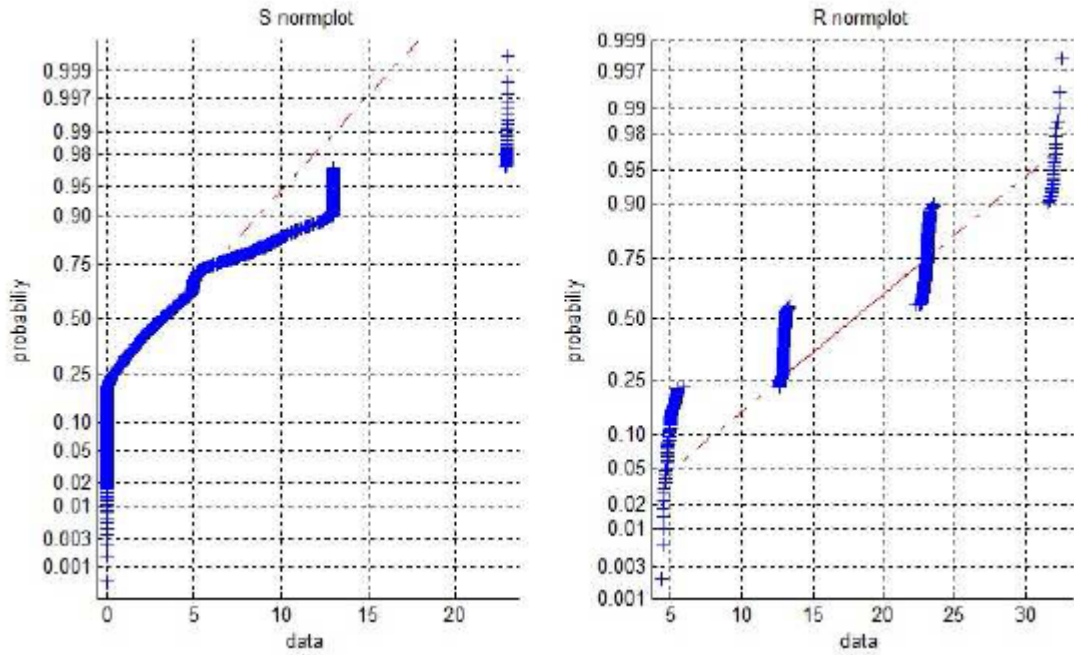
Figure A.1: *normal probability plots of both the superposition (S) and the mixture distribution (R)*

Additionally, in figure A.2, the cumulative function plots of the above distributions are depicted and they are also different from each other.
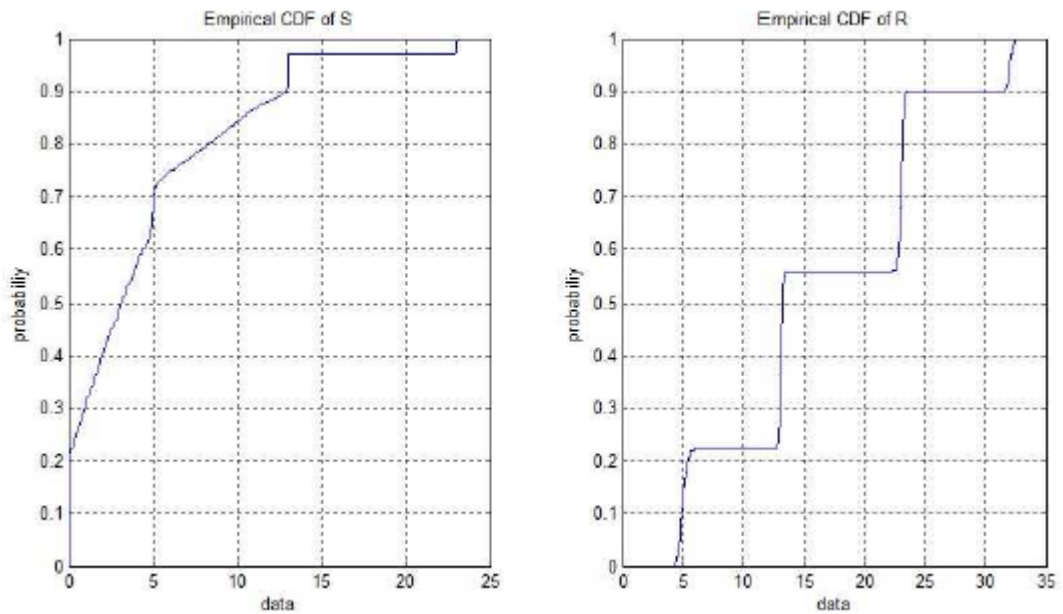

Figure A.2: *Cumulative function plots of both the superposition (S) and the mixture distribution (R)*

Thus, the mixture distribution is not the appropriate model to implement in order to have an analytical expression for the superposition of normal distributions with random variables their interarrival times.

A.2. Code of the example

```
%X1~N(13,0.02)  X2~N(32,0.05)  X3~N(5,0.08) X4~N(23,0.04)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
close all;
clear all;
clc;
N=1000;%number of random numbers created by mixture distribution
w1=0.3;w2=0.1;w3=0.2;w4=0.4;%weight p=[0 1]
%%%Generate a normal sample of normal distribution X1
n1=normrnd(13,0.02,[1,N*w1]);
for i=1:N*w1-1
    n1(i+1)=n1(i)+n1(i+1);
end
%%%Generate a normal sample of normal distribution X2
n2=normrnd(32,0.05,[1,N*w2]);
for i=1:N*w2-1
    n2(i+1)=n2(i)+n2(i+1);
end
%%%Generate a normal sample of normal distribution X3
n3=normrnd(5,0.08,[1,N*w3]);
for i=1:N*w3-1
    n3(i+1)=n3(i)+n3(i+1);
end
%%%Generate a normal sample of normal distribution X3
n4=normrnd(23,0.04,[1,N*w4]);
for i=1:N*w3-1
    n4(i+1)=n4(i)+n4(i+1);
end
%put all the generated random numbers from each distribution together
n=[n1 n2 n3 n4];
%sort in ascending order
n1n2n3n4=sort(n);
%%%%S->INTERARRIVAL TIMES OF MIXTURE DISTRIBUTION
S=[];
for i=1:N-1
   S(i+1)=abs(n1n2n3n4(i+1)-n1n2n3n4(i));
end
%Gaussian mixture distribution with 2 components in 1 dimension
mu = [13;32;5;23];
sigma = cat(3,[.02],[.05],[.08],[0.04]);
%p = ones(2,1)/2;
p=[w1;w2;w3;w4];
obj = gmdistribution(mu,sigma,p);
%generate N random numbers(->INTERARRIVAL TIMES) of obj distribution and
put them in
%an array
R=[];
for i=1:N/4
   r=random(obj);
   R=[R r]
end
```

```
%NORMPLOT S-R%
figure(1);subplot(2,2,1);
normplot(S);
xlabel('data');ylabel('probabiliy');title('S normplot');
subplot(2,2,2);
normplot(R);
xlabel('data');ylabel('probabiliy');title('R normplot');
subplot(2,2,[3 4]);
normplot(S);hold on;normplot(R);
xlabel('data');ylabel('probabiliy');title('S/R normplot');
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%cdfplot S-R
figure(2); subplot(2,2,1);cdfplot(S);
xlabel('data');ylabel('probabiliy');title('Empirical CDF of S');
subplot(2,2,2);cdfplot(R);
xlabel('data');ylabel('probabiliy');title('Empirical CDF of R');
subplot(2,2,[3 4]);
cdfplot(S);hold on;cdfplot(R);
xlabel('data');ylabel('probabiliy');title('Empirical CDF of S/R');
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

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