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GESTION DE LA QUALITÉ DE SERVICE ET PLANIFICATION OPTIMALE DE RÉSEAUX DE CAPTEURS MULTIMÉDIA SANS FIL

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à doña Judith,
la autora de mis días…

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RÉSUMÉ

Un Réseau de capteurs sans fil (RCSF) est constitué d'un certain nombre d'entités (capteurs) géographiquement dispersées, de taille réduite, avec une autonomie et une puissance de traitement réduites. Ces dispositifs sont utilisés pour réaliser, de manière indépendante, des tâches comme la surveillance, le contrôle de processus industriel, etc. Les avancées en microélectronique ont conduit à l'émergence des petites caméras (type Complimentary Metal Oxide Silicon (CMOS)) et microphones accessibles. Ces capteurs audio-visuels peuvent être intégrés dans un RCSF pour former des Réseau de capteurs multimédia sans fil (RCMSF). Dans certains types d'applications, comme la surveillance des frontières, un grand nombre de ce type de capteurs est susceptible d'être déployés, sur de vastes terrains. Un volume considérable de flux audio-visuel (en plus des données) doit être transmis au centre de contrôle (le collecteur, ou *SINK*) pour analyse et prise de décision. Il y a donc un besoin important en termes de bande passante, avec surtout une forte contrainte en termes de délai de transmission et d'autres paramètres de RCSF. Des solutions pour le routage d'information ont été développées pour des RCSF, mais ces protocoles n'ont pas pris en compte la génération à grande échelle des données multimédia, elles sont par conséquent inadaptées aux RCMSF.

Les capteurs typiquement sont *omnidirectionnels*, c'est-à-dire qu'ils sont capables de capter des signaux qui proviennent de toutes les directions autour d'eux. Les capteurs multimédia, en particulier les capteurs de vidéo, sont de type *directionnel*. Pour ce type de capteurs, l'aire de captage est limitée à un secteur donné d'un plan tridimensionnel. Malheureusement, les modèles mathématiques développés pour le placement des RCMSF conventionnels ne peuvent pas être appliqués dans le cadre de la configuration et de la planification des réseaux de capteurs directionnels. De nouveaux modèles d'optimisation sont donc nécessaires pour la capture des principaux paramètres caractérisant les capteurs directionnels.

Dans cette thèse, nous abordons donc les problèmes clés suivants : le routage des données hétérogènes (scalaires et multimédia) pour les nœuds d'un RCMSF afin d'assurer une meilleure Qualité de Service (QdS) aux usagers ; et le déploiement optimisé de capteurs directionnels d'un RCMSF dans un espace tridimensionnel dont le but est couvrir un ensemble de points d'intérêts définis dans tel espace. Notre thèse se compose de trois articles scientifiques, chacun traitant d'une problématique bien spécifique.

Le premier article traite du problème du routage d'information pour les RCMSF basé sur la QdS. Nous proposons un nouveau protocole, *AntSensNet*, basé sur l'heuristique de la colonie de fourmis, qui utilise plusieurs métriques de QdS pour trouver de bonnes routes pour les données multimédia et l'information scalaire. Dans la pratique, le protocole établit

d'abord une structure hiérarchique sur le réseau avant de choisir les chemins appropriés pour répondre aux diverses exigences de QdS des différents types de trafic qui circulent dans le réseau. Ceci permet de maximiser l'utilisation des ressources du réseau, tout en améliorant la performance de la transmission de l'information. En outre, *AntSensNet* est capable d'utiliser un mécanisme efficace d'ordonnancement de paquets et de multiples chemins afin d'obtenir la distorsion minimale au moment où une application fait la transmission de la vidéo dans le réseau.

Dans le deuxième article nous continuons avec le sujet de la QdS dans le RCMSFs et, plus spécifiquement, nous abordons la problématique du contrôle d'admission pour ce type de réseau. Grâce au contrôle d'admission, il est possible de déterminer si un réseau est capable de supporter un nouveau flot de données. S'il n'y a pas de contrôle d'admission dans un RCMSF, le performance du réseau sera compromis car les ressources existantes dans le réseau ne seront pas assez pour tous les flots acceptés et cela entraînera beaucoup de problèmes comme la perte de paquets des flots. Nous proposons un nouveau schéma de contrôle d'admission de nouveaux flots multimédia pour un RCMSF. Le système proposé est en mesure de déterminer si un flot de données puisse être admis dans le réseau, compte tenu de l'état actuel des liaisons de communications et l'énergie des nœuds. La décision sur l'acceptation est prise de manière distribuée, sans utiliser une entité centrale. De plus, notre schéma se présente comme un *plug-in*, et est adaptable à d'éventuels protocoles de routage et MAC utilisés pour la transmission de données dans les RCMSF. Nos résultats de simulation montrent l'efficacité de notre approche pour répondre aux exigences de QdS des nouveaux flots de données.

Finalement, notre troisième article traite du problème du déploiement optimal des capteurs multimédia dans un espace 3D. Tel que mentionné ci-dessus, la plupart des capteurs multimédia sont du type directionnel. De surcroît, ces capteurs sont plus coûteux et plus spécialisés que les capteurs scalaires. En conséquence, les déploiements aléatoires, qui sont typiques pour les capteurs scalaires, ne sont ni souhaitables ni adéquats pour les capteurs multimédia. A cet effet, nous proposons un modèle optimal de déploiement 3D de capteurs directionnels. Ce modèle vise à déterminer le nombre minimum de capteurs directionnels connectés, leur emplacement et leur configuration, qui sont nécessaires pour couvrir un ensemble de points de contrôle dans un espace 3D donné. La configuration de chaque capteur déployé est déterminée par trois paramètres : la plage de détection, le champ de vision (Field of View (FoV)) et l'orientation. Nous présentons une formulation "*Integer Linear Programming*" (ILP) pour trouver la solution exacte du problème et aussi, un algorithme glouton capable de trouver une solution approximative (mais efficace) du problème. Nous évaluons également différentes propriétés des solutions proposées par le biais de nombreuses simulations.

Avec ces trois articles on a réussi à résoudre, d'une façon à la fois innovatrice et pratique, les problèmes de routage basé sur la QdS pour les RCMSF et le déploiement de capteurs directionnels, qui sont l'objectif principal de notre recherche.

ABSTRACT

A Wireless Sensor Network (WSN) consists of a set of embedded processing units, called sensors, communicating via wireless links, whose main function is the collection of parameters related to the surrounding environment, such as temperature, pressure or the presence/motion of objects. WSN are expected to have many applications in various fields, such as industrial processes, military surveillance, observation and monitoring of habitat, etc. The availability of inexpensive hardware such as CMOS cameras and microphones that are able to ubiquitously capture multimedia content from the environment has fostered the development of Wireless Multimedia Sensor Networks (WMSNs), i.e., networks of wirelessly interconnected devices that allow retrieving video and audio streams, still images, and scalar sensor data. In addition to the ability to retrieve multimedia data, WMSNs will be able to store, process in real time, correlate and fuse multimedia data originated from heterogeneous sources, and perform actions on the environment based on the content gathered. Many applications require the sensor network paradigm to be rethought in view of the need for mechanisms to deliver multimedia content with a certain level of quality of service (QoS). Due to high bandwidth, processing and stringent Qos requirements existing solutions are not feasible for WMSNs. Since the need to minimize the energy consumption has driven most of the research in sensor networks so far, there is a need to create mechanisms to efficiently deliver application-level QoS, and to map these requirements to network-layer metrics such as latency or delay.

Additionally, in WSNs, an omnidirectional sensing model is often assumed where each sensor can equally detect its environment in each direction. Instead, multimedia sensors, specially video sensor, are directional sensors. A directional sensor is characterized by its sensing region which can be viewed as a sector in a three-dimensional plane. Therefore, it can only choose one active sector (or direction) at any time instant. Unfortunately, the many methods developed for deploying traditional WSNs cannot directly be used for optimizing and configuring directional WMSNs due to the different parameters involved. Therefore, new optimization models which capture the primary parameters characterizing directional sensors are necessary.

The issues aforementioned are crucial challenges for the development of WMSNs. In this thesis, we are interested in the following aspects: routing of heterogeneous data (scalar and multimedia) from the nodes of a WMSN to the sink in order to provide better QoS experience to users; and an optimized deployment of directional sensors of a WMSN in a three-dimensional surface with the objective to cover all the control points as defined in such a space. Our thesis runs through three scientific papers, each addressing a specific problem.

In our first paper, we address the problem of data routing based on different QoS metrics in a WMSN. We propose a new protocol *AntSensNet*, based on the traditional ant-based algorithm. The AntSensNet protocol builds a hierarchical structure on the network before choosing suitable paths to meet various QoS requirements from different kinds of traffic, thus maximizing network utilization, while improving its performance. In addition, AntSensNet is able to use a efficient multipath video packet scheduling in order to get minimum video distortion transmission.

In the second paper, we address the problem of connection admission control for WMSNs. With admission control, it is possible to determine whether a network is capable of supporting a new data stream. Without admission control in a WMSN, the network performance will be compromised because the existing resources within the network cannot be enough for all the flows accepted and this will cause many problems such as packet loss and congestion. Taking multiple parameters into account, we propose a novel connection admission control scheme for the multimedia traffic circulating in the network. The proposed scheme is able to determine if a new flow can be admitted in the network considering the current link states and the energy of the nodes. The decision about accepting is taken in a distributed way, without trusting in a central entity to take this decision. In addition, our scheme works like a plug-in, being easily adaptable to any routing and MAC protocols. Our simulation results show the effectiveness of our approach to satisfy QoS requirements of flows and achieve fair bandwidth utilization and low jitter.

Finally, in the third paper, we address the problem of optimal deployment of directional sensors in a 3D space. We have already mentioned that conventional methods to deploy omnidirectional sensors are not suitable to deploy directional sensors. To remedy this deficiency, we propose a mathematical model which aims at to determine the minimum number of connected directional multimedia sensor nodes and their configuration, needed to cover a set of control points in a given 3D space. The configuration of each deployed sensor is determined by three parameters: sensing range, field of view and orientation. We present the exact ILP formulation for the problem and an approximate (but computationally efficient) greedy algorithm solution. We also evaluate different properties of the proposed solutions through extensive simulations.

Overall, the proposed solutions in this thesis are both innovative and practical. With these three papers, we have been successfully resolved the problems of a QoS-based routing protocol for WMSN and an optimal deployment of directional sensors in a 3D space, which are the components of the main objective of this thesis.

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LISTE DES SIGLES ET ABRÉVIATIONS

WSN	Wireless Sensor Network
WMSN	Wireless Multimedia Sensor Network
CMOS	Complimentary Metal Oxide Silicon
MEMS	Micro-Electro-Mechanical System
QdS	Qualité de Service
QoS	Quality of Service
FoV	Field of View
RCSF	Réseau de capteurs sans fil
RCMSF	Réseau de capteurs multimédia sans fil
ILP	Integer Linear Programming
ACO	Ant Colony Optimization
FEC	Forward Error Correction
WFQ	Weighted Fair Queuing
MANET	Mobile Ad-hoc Networks
FANT	Forward Ant
BANT	Backward Ant
CH	Cluster Head
M3DSP	Minimum 3D Directional Sensor Placement
CAC	Connection Admission Control

CHAPITRE 1

INTRODUCTION

Un RCSF est un système constitué de plusieurs dizaines à plusieurs centaines de nœuds interconnectés, constitués chacun d'un capteur, d'une unité de traitement de l'information et d'un bloc de communication (Akyildiz *et al.*, 2002). Les nœuds disposent d'une zone de couverture extrêmement réduite et sont déployés d'une manière dense dans des environnements hétérogènes. Ils sont autonomes et disposent pour cela d'une réserve énergétique, dont le renouvellement peut s'avérer impossible, ce qui limite leur durée de vie. Chacun des nœuds doit être en mesure de traiter les données reçues, de prendre une décision locale et de la communiquer de façon autonome aux nœuds voisins auxquels il est connecté. Cette coopération est destinée à assurer les meilleures prises de décision possibles malgré les limites en termes de consommation énergétique et de puissance de traitement. En effet, les RCSF sont assujettis à des contraintes fortes et de natures multiples, énergétique et calculatoire entre autres, ce qui limite les capacités de traitement et de communication des nœuds du réseau. Étant donné la rapide miniaturisation du matériel, un petit capteur peut être équipé de modules de collecte d'information visuelle et d'audio. Ces capteurs sont habilités à capturer du contenu multimédia (vidéo, son, images) de l'environnement, ce qui a facilité le développement des RCMSF. Ce nouveau type de réseau améliorera les applications déjà existantes des réseaux de capteurs (telles que la domotique ou la surveillance), mais aussi permettra la réalisation d'applications vraiment novatrices, comme des nouveaux services de localisation de personnes, le contrôle environnemental ou l'assistance aux personnes âgées.

Cette diversité d'applications amène ces réseaux à supporter différents types de trafics et à fournir des services qui doivent être à la fois génériques et adaptatifs aux applications car les propriétés de la QdS différent d'un type d'applications à un autre. Néanmoins, jusqu'à présent, le besoin de réduire au minimum la consommation d'énergie a fait objet de la plupart des recherches des RCSF. Peu d'études dans le domaine concernent les mécanismes pour délivrer efficacement la QdS au niveau applicatif à partir de métriques de niveaux réseau et liaison comme le délai ou la bande passante. Dans cet ordre d'idées, nous allons nous intéresser dans cette thèse aux mécanismes d'implantation de la QdS pour le RCMSF et comment déployer ce type de réseau. Dans ce chapitre, nous commencerons par donner une brève description des réseaux de capteurs multimédia, leurs applications et leurs principaux défis. Ensuite, nous présenterons quelques éléments de la problématique, liés principalement au routage basé sur la QdS. Puis, nous détaillerons nos objectifs de recherche et enfin, nous présenterons le plan de cette thèse.

1.1 Définitions et concepts de base

Les RCSF sont un type spécial de réseau Ad-hoc, dans lesquels les nœuds sont des «capteurs». Ils se composent généralement d'un grand nombre de capteurs communicants entre eux via des liens radio pour le partage d'information et le traitement coopératif. Dans ce type de réseau, les capteurs échangent des informations par exemple sur l'environnement pour construire une vue globale de la région contrôlée, qui est rendue accessible à l'usager externe par un ou plusieurs nœud(s). Les données collectées par ces capteurs sont acheminées directement ou via un chemin multi-sauts formé d'autres capteurs à un « point de collecte », appelé station de base (ou SINK). Cette dernière peut être connectée à une machine puissante via internet ou par satellite (Wang et Balasingham, 2010).

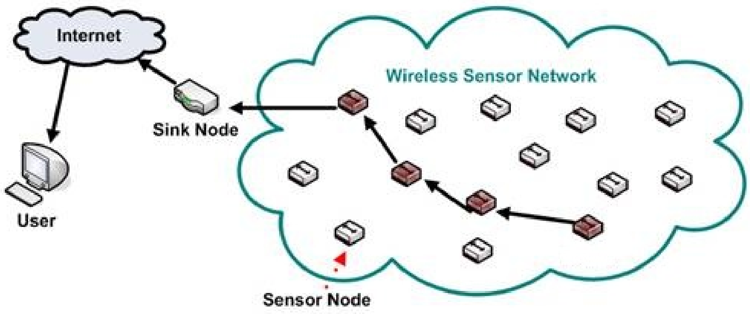

Figure 1.1 Un exemple d'un RCSF

Un exemple de réseaux de capteurs est fourni dans la Figure 1.1 : les capteurs sont déployés d'une manière aléatoire dans une zone d'intérêt, et une station de base, située à l'extrémité de cette zone, est chargée de récupérer les données collectées par les capteurs. Lorsqu'un capteur détecte un événement pertinent, un message d'alerte est envoyé à la station de base par le biais d'une communication entre les capteurs. Les capteurs sont généralement équipés de faibles ressources (CPU, mémoire, etc.) et de source d'énergie limitée. La station de base et les machines de l'usager sont généralement munis de puissance de calcul et de source d'énergie supérieures à celles des capteurs. En plus, un RCSF présente les caractéristiques suivantes (Akyildiz et Vuran, 2010) :

absence d'infrastructure - les réseaux Ad-hoc en général, et les réseaux de capteurs en particulier se distinguent des autres réseaux par la propriété d'absence d'infrastructure préexistante et de tout genre d'administration centralisée.

taille importante - un réseau de capteurs peut contenir des milliers de noeuds.

topologie dynamique - les capteurs peuvent être attachés à des objets mobiles qui se déplacent d'une façon libre et arbitraire rendant ainsi la topologie du réseau fréquemment changeante.

bande passante limitée - une des caractéristiques primordiales des réseaux basés sur la communication sans fil est l'utilisation d'un médium de communication partagé. Ce partage fait que la bande passante réservée à un noeud est limitée.

contrainte d'énergie, de stockage et de calcul - la caractéristique la plus critique dans les réseaux de capteurs est la limitation de ses ressources énergétiques car chaque capteur du réseau possède de faibles ressources en termes d'énergie (batterie). Afin de prolonger la durée de vie du réseau, une minimisation des dépenses énergétiques est exigée chez chaque noeud. Ainsi, la capacité de stockage et la puissance de calcul sont limitées dans un capteur.Pour cette raison, il est important de disposer de protocoles de routage efficaces en termes de conservation d'énergie.

Les RCSF sont généralement déployés en grand nombre dans une zone géographique où ils vont capter, mesurer et rapporter certains phénomènes physiques. Ils peuvent donc servir à la surveillance de leur environnement physique ainsi qu'à la surveillance de zones, la détection d'intrusion, la détection de feu, la surveillance d'infrastructures civiles ou encore à l'analyse climatique. Ils peuvent également être utilisés pour surveiller des habitations et contribuer au confort domestique, en transformant les logements en environnements intelligents dont les paramètres (température, pression, humidité, luminosité, etc.) s'adaptent automatiquement au comportement des individus (Li *et al.*, 2008).

L'évolution récente de la technologie a permis de passer d'un modèle où les capteurs sans fil étaient principalement dédiés à la mesure de paramètres environnementaux simples comme la température ou l'humidité à des capteurs équipés de capacités multimédia. En effet, la disponibilité de matériel et dispositifs abordables tels que les caméras et microphones CMOS permettent aujourd'hui d'embarquer dans un capteur des caméras et des microphones. Cyclops (Rahimi *et al.*, 2005) et Stargate (Figure 1.2) sont deux exemples concrets de ce type de capteurs multimédias communicants.

Ces capteurs font partie d'un réseau de capteurs multimédia sans fil (RCMSF). Un RCMSF est un réseau de dispositifs interconnectés d'une manière sans fil qui permet d'obtenir des flots d'audio et de vidéo, même d'images et de données scalaires (Akyildiz *et al.*, 2007). Comme conséquence de cette définition, on peut donc conclure que les composantes d'un RCMSF sont capables de capter des données scalaires de l'environnement (tels que la température, la pression ou le niveau de lumière) mais aussi des vidéos ou des sons ou des images autour de lui. En outre, les réseaux seront en mesure de stocker, de traiter en temps réel, de corréler et de fusionner des donnés multimédias provenant de sources hétérogènes. Bien

Figure 1.2 Un capteur de vidéo *Stargate*

que les RCMSFs héritent des mêmes problèmes et limitations des RCSFs, ils permettront d'améliorer les applications déjà existantes sur les RCSF telles que le suivi de personnes, la domotique, et la surveillance de l'environnement, mais également le développement de nouvelles applications telles que :

- *Surveillance multimédia :* Les capteurs de vidéo et d'audio compléteront et amélioreront les systèmes actuels de surveillance contre le crime et le terrorisme. Les RCMSFs aussi permettront de contrôler des frontières, des événements publics et des propriétés privées. Ces capteurs peuvent inférer et enregistrer des activités potentiellement pertinentes (telles que des vols, des accidents de voitures ou des violations de trafic) et produire des flots d'audio-vidéo pour de futures enquêtes.
- *Trafic :* Il sera possible de surveiller le trafic dans les rues des grandes villes et d'offrir des services qui aident les conducteurs à éviter des congestions.
- *Services de localisation de personnes :* Le contenu multimédia (tel que des vidéos ou des images), accompagné avec des techniques avancées de traitement de signaux, sera utilisé pour localiser des personnes disparues ou même pour identifier des criminels ou des terroristes dans les aéroports ou les terminaux.
- *Télémédicine :* Les capteurs de télémédicine peuvent être intégrés avec des réseaux multimédia 3G ou 4G pour fournir des services ubiquitaire de santé. Les patients porteront des capteurs médicaux pour surveiller des paramètres tels que la température du corps, la pression artérielle, l'oxymétrie pulsée, l'ECG, et l'activité respiratoire. De plus, les centres de santé pourront réaliser des contrôles à distance de leur patients via des capteurs d'audio ou de mouvement, qui se trouvent implantés dans leur corps.

Un autre élément différenciateur entre un RCSF et un RCMSF est le modèle de captation qui est utilisé par les capteurs qui font partie de ces réseaux. Les capteurs scalaires, c'est-à-dire, les capteurs de température ou de pression ou de lumière, suivent le modèle omnidirectionnel. Pour ce modèle, l'information captée par le capteur provient de toutes les directions autour de lui. Par contre, un capteur d'audio ou de vidéo a une perception sectorielle. Ces capteurs multimédia sont de puissants capteurs multidimensionnels qui permettent de capturer une vue directionnelle d'un terrain ou d'une région d'intérêt, généralement appelé champ de vision (FoV) (Osais *et al.*, 2010). Ce champ de vision est défini par des paramètres importants, dont quelques uns sont présentés à la Figure 1.3 (Tezcan et Wang, 2008). Le problème fondamental pour les capteurs directionnels est celui de la couverture de points d'intérêt, c'est-à-dire, de trouver la configuration optimale pour les paramètres du champ de vision de chaque capteur directionnel permettant minimiser le nombre de capteurs nécessaires pour couvrir un ensemble de points d'intérêt dispersés dans une zone donnée.

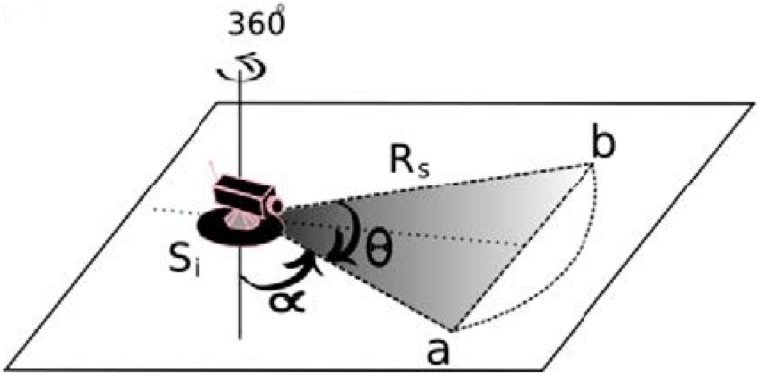

Figure 1.3 Les paramètres de la configuration d'un capteur directionnel : α = angle avec la verticale, θ = ouverture de la caméra, R_s = rayon de détection

1.2 Éléments de la problématique

Comme présentées dans les sections antérieures, les applications pour les RCMSF sont nombreuses, et au fur et à mesure que la technologie évolue, ces applications se multiplieront. Dans certains types d'applications, comme la surveillance des frontières, un grand nombre de ce type de capteurs est susceptible d'être déployés, sur de vastes terrains. Dans ce cas un grand nombre de flots audio-visuels (en plus des données) sont transmis au centre de contrôle (station de base, ou SINK) pour analyse et prise de décision. Il y a donc un besoin important en termes de bande passante, avec surtout une forte contrainte en termes de délai de transmission. Les solutions existantes ont été développées pour des RCSF mais ne prennent pas en compte la génération à grande échelle de données multimédia, ce qui les rend inadaptées aux RCMSF. Pour ces raisons, le paradigme des RCSF doit être repensé et intégrer des mécanismes permettant la transmission de contenu multimédia avec un certain degré de QdS.

La conservation de l'énergie des capteurs et le maintien du réseau fonctionnel le plus longtemps possible sont donc des défis importants qui sont posés par les RCSFs classiques. La plupart d'algorithmes et protocoles valables pour les RCSFs utilisent cette contrainte énergétique comme l'élément principal de leur conception et fonctionnement (Akkaya et Younis, 2005b). Malgré ces nombreuses approches recensées dans la littérature, force est de constater que le problème du support de la QdS pour les RCMSF est encore un problème ouvert et sans une solution satisfaisante.

Voici la liste des problemes que la QdS doit faire face dans les RCMSFs.

- **Des mécanismes de contrôle d'admission inadéquats.** Quand un nœud a besoin de générer un nouveau flot de données multimédia vers le SINK, des processus sont nécessaires pour savoir si le réseau a assez de ressources pour satisfaire les exigences de ce flot, en termes de bande passante, de capacité des liens de communication ou de délai de bout en bout par exemple. Les paradigmes de contrôle d'admission trouvés dans la littérature (notamment les articles (Perillo et Heinzelman, 2003) et (Yin *et al.*, 2010)) sont inadéquats pour les exigences des flots multimédia où les schémas proposés par les auteurs ne sont pas assez généraux pour prendre en compte des demandes de ressources des nouvelles applications multimédia qui peuvent résider dans un RCMSF. Généralement, ces solutions ne considèrent que la consommation de l'énergie pour admettre un nouveau flot, tandis que d'autres importants aspects comme la bande passante, le délai de bout en bout ou la gigue ne sont pas pris en compte. Il y a donc nécessité de concevoir des algorithmes pour le contrôle d'admission dans les RCMSF.
- **L'absence d'un protocole de support de la QdS pour les réseaux de capteurs multimédia.** Comme nous l'avons déjà mentionné, il y a beaucoup de protocoles de routages pour les RCSFs. Et au fur et à mesure que les RCMSFs se rendent plus populaires, il est très probable que le nombre de ces protocoles augmente. Toutefois, à notre connaissance, aucun de ces protocoles ne résout bel et bien les problèmes courants et futurs liés à la transmission de l'information multimédia dans un RCMSF.Parmi les principaux défis, on trouve les suivants :
  - **Le support insuffisant pour le trafic hétérogène.** Le trafic multimédia requiert un haut niveau d'hétérogénéité car il est constitué de vidéo, d'audio, et d'images. De plus, il faut tenir compte du fait que le trafic dans un réseau de capteurs inclut aussi des données scalaires (comme la température, la lumière, etc.) qui sont captées par les capteurs scalaires déployés dans le réseau. Autrement dit, dans le réseau, circulent différents types de trafic que sont l'information multimédia et l'information scalaire. Dans la littérature, on trouve que les protocoles conçus pour la transmission de la vidéo (comme ceux proposés par Chen *et al.* (2007a) ou Politis *et al.* (2008)) ne

prennent en compte ni de multiples priorités ni l'existence de trafic hétérogène. Par ailleurs, les protocoles qui ont été créés pour faire la différenciation des divers types de trafic, ne tiennent pas compte des particularités et spécificités de l'information multimédia qui circule dans le réseau. En conséquence, un nouveau protocole est nécessaire et doit être capable de manipuler et classifier les types de trafic, et d'établir les priorités en fonction des exigences des applications.

- **L'incapacité de supporter la communication en temps réel.** C'est normal d'avoir dans les RCMSFs de la diffusion de vidéo ou d'audio en mode continu (*streaming*). Cela exige que le protocole fournisse de la QdS pour la communication en temps réel. Bien que les protocoles *SPEED* (He *et al.*, 2003) et *MMSPEED* (Felemban *et al.*, 2006) supportent le concept de temps réel à travers du paradigme de vitesse de données (de cette façon, l'application et les nœuds intermédiaires peuvent calculer le temps d'arrivée d'un paquet au SINK), le besoin de vrai schémas de transmission en temps réel pour le RCMSF, qui assurent des communications avec de stricts délais, existe. Ces besoins sont couramment ressentis lors de la transmission de la vidéo ou de l'audio. D'autres approches existent dans la littérature. Par exemple, Chenyang *et al.* (2002) proposent une solution pour la transmission de données dans des délais stricts avec une utilisation efficace de l'énergie, mais les auteurs ne considèrent pas certains éléments importants de la communication multimédia : l'existence de différentes types de trafic et la qualité de service pour les données. Pour cette raison, ce protocole est inadéquat pour la transmission de données multimédia dans un RCMSF.
- **Le déficit de support pour la QdS basée sur les conditions du réseau.** Il existe dans le réseau plusieurs conditions qui affectent le choix d'une route. Parmi ces conditions, on peut citer : l'énergie résiduelle des nœuds intermédiaires, la congestion d'un lien sans fil, la taille de la file de données dans un nœud, etc. Une décision de routage basée sur ces métriques peut éliminer des routes qui ne supporteront pas des transmissions avec une bande passante élevée ou qui introduiront des retransmissions (et généreront des congestions) dues aux mauvaises conditions du canal.

  Le protocole proposé par Akkaya et Younis (2005a) est un bon exemple d'un protocole qui s'adapte aux conditions du réseau. Cependant, le protocole a besoin d'améliorations par rapport à l'utilisation de la mémoire des nœuds et la nécessité de connaître toute la topologie du réseau afin d'obtenir de bonnes routes. A défaut de ces améliorations, il sera très difficile de l'implanter.

  Les protocoles basés sur l'optimisation de colonies de fourmis (Zheng *et al.*, 2004; Sivajothi et Naganathan, 2008; Rosati *et al.*, 2007) offrent le support pour trouver des routes en se basant sur de multiples métriques de qualité de service. Ces protocoles tiennent compte de l'état des nœuds du réseau et de ses liens pour transmettre les paquets. En plus, cette adaptabilité aux conditions du réseau leur permet d'améliorer le « temps de vie » du réseau et de balancer la charge de routage sur un nombre plus grand de nœuds. Toutefois, ces protocoles ne prennent pas en compte la diversité du trafic dans les réseaux de capteurs multimédia et ne sont capables de gérer les priorités de ce trafic. Enfin, il n'existe pas une façon de spécifier le poids de chaque métrique dans les décisions de routage, c'est-à-dire, ces protocoles n'ont pas l'habilité de spécifier l'importance de chaque métrique de QdS sur la route choisie.

Il y a donc un besoin de protocole qui prend en compte les conditions du réseau, mais aussi, qui permet à la couche application de spécifier quelques métriques additionnelles (comme la bande passante, etc.) et leurs poids respectifs au moment de trouver de bonnes routes. A notre connaissance, il n'existe pas encore de protocole qui soit capable de trouver des routes à partir de plusieurs métriques en même temps et qui tienne compte des paramètres stipulés par les applications.

- **Le déploiement de capteurs multimédia directionnels.** La plupart des applications entrevues pour les RCMSF nécessitent au préalable un placement optimal des capteurs multimédia dans l'environnement. En effet, ces applications des réseaux de capteurs tout comme certaines autres nécessitent un placement des capteurs qui permet une couverture optimale de la zone à surveiller. Plusieurs techniques de placement optimal de capteurs ont été proposées dans la littérature (Younis et Akkaya, 2008). Cependant celle-ci le sont pour des capteurs scalaires (i.e. capteurs avec des capacités de capture omnidirectionnelles) et homogènes (i.e. étendu de la couverture du capteur). Osais *et al.* (2010) propose un algorithme pour les capteurs directionnels, mais il considère seulement un déploiement homogène au niveau du sol, et cela n'est pas réaliste pour la plupart des capteurs de vidéo ou d'audio. Par ailleurs, les réseaux de capteurs multimédia sont par essence hétérogènes (i.e. Puissance du microphone et zoom de la caméra) et directionnels (i.e. angle d'ouverture de la caméra ou du microphone) ce qui les rend complètement différents des capteurs scalaires. Ces deux caractéristiques (hétérogénéité et capture directionnelle) rendent le problème de placement plus complexe que ce que nous avions avec les capteurs scalaires. Les techniques de placement optimales proposées précédemment dans la littérature ne peuvent donc pas être utilisées directement. Un schéma spécifique pour le placement optimisé de capteurs multimédia directionnels en fonction de leurs capacités est donc nécessaire. Celle-ci devra permettre de placer les capteurs multimédia communicants dans le but de couvrir de façon optimale une zone visée.

1.3 Objectifs de recherche

L'objectif principal de cette thèse est de concevoir des mécanismes efficaces pour la gestions et le support de la qualité de services (QdS) dans les réseaux de capteurs multimédia sans fil (RCMSF) en mettant l'accent sur le processus de routage et de déploiement. De manière plus spécifique, cette thèse vise à :

1. Analyser les solutions proposées dans la littérature pour le routage et la gestion de la QdS, dans les RCSFs et les RCMSF, ainsi que les mécanismes proposés pour le déploiement de capteurs. Le but est d'en ressortir les faiblesses et les limitations qui ne sont pas encore résolues adéquatement.
2. Proposer un nouveau protocole de routage adaptative pour les RCMSFs. Le protocole garantira des métriques diverses de QdS, telles que : a) une bande passante, b) un faible taux de pertes, c) un délai spécifique et d) une gigue minimale, tout en minimisant la consommation d'énergie des nœuds capteurs qui font partie du réseau.
3. Évaluer la performance du protocole proposé au point précédent en le comparant aux principaux modèles recensés dans la littérature.
4. Proposer une stratégie de contrôle d'admission pour les RCMSF. Cette stratégie permettra d'assurer que tout nouveau flot de données multimédia généré dans le réseau aura toutes les ressources nécessaires à son acheminement. Dans le cas contraire, il n'y sera pas admis.
5. Concevoir un modèle mathématique pour le problème du déploiement de capteurs directionnels couvrant un ensemble de points d'intérêt dans un espace tri-dimensionnel.
6. Développer une solution heuristique pour le problème posé au point précédent et mesurer la qualité des solutions obtenues.

1.4 Principales contributions de la thèse et leur originalité

Les principales contributions de cette thèse s'articulent autour de deux grands axes qui sont : la conception d'un protocole de routage et transmission de données pour les RCMSF basé sur la QdS et qui prend en compte les conditions du réseau, et la proposition d'un cadre de résolution du problème du placement optimal de capteurs multimédia directionnels. Ces deux principales contributions aident à la résolution de deux problématiques qui constituent des défis importants pour les systèmes de réseaux de capteurs multimédia. Ces contributions peuvent être détaillées comme suit :

1. **Nouveau protocole pour le routage et la transmission de données dans un RCMSF :** Nous avons conçu un protocole pour les RCMSF, basé sur la gestion de

la QdS et qui utilise l'heuristique de la colonie de fourmis pour trouver les meilleures routes pour un flot d'information donné. Dans un premier temps, le protocole utilise un mécanisme inspiré du comportement des fourmis pour créer de grappes dans le réseau. Notre algorithme de formation de grappes pour les RCMSF est original et il surpasse en efficacité les autres schémas très connus comme HEED (Younis et Fahmy, 2004) ou LEACH (Xiangning et Yulin, 2007). En plus d'utiliser des fourmis pour trouver des routes entre les têtes de grappe et le SINK en utilisant de multiples métriques de QdS, le protocole considère des classes de trafic et est capable de prioriser un trafic à partir des exigences de la couche application. Finalement, le protocole utilise des méthodes spéciales pour diminuer la distorsion de la vidéo transmise par les nœuds d'une route. A notre connaissance, c'est la première fois qu'un protocole avec toutes ces caractéristiques est proposé pour les RCMSF, contrairement aux approches existantes qui ne considèrent pas tous ces éléments en même temps.

2. **Nouveau algorithme réparti pour le contrôle d'admission :** Nous avons proposé un algorithme réparti qui permet de déterminer si les ressources du réseau sont suffisantes pour admettre un nouveau flot de données multimédia. Ce qui est original dans notre approche est l'utilisation de multiples paramètres de QdS afin que la couche application spécifie des exigences de QdS pour le nouveau flot à générer. La plupart des approches de contrôle d'admission tient compte d'un ou maximum de deux éléments de la QdS pour savoir si le flot doit être admis ou pas. De plus, notre approche est répartie et indépendante de la couche réseau, ce qui permet une facilité d'adaptation de notre algorithme à n'importe quel protocole de la couche réseau utilisé par le RCMSF.
3. **Solution au problème de placement optimale des capteurs directionnels dans un espace 3D sous contraintes de couverture et de connectivité :** Nous avons modélisé le problème de déploiement des capteurs directionnels dans un RCMSF dans un espace 3D, dans le but de minimiser le nombre de capteurs déployés sous la double contrainte de couverture et connectivité totale du réseau déployé. Notre modèle peut servir comme une borne supérieure pour des solutions heuristiques. En plus, nous avons proposé une méthode gloutonne pour trouver des bonnes solutions au problème dans des temps raisonnables. À notre connaissance, un modèle pour ce problème et un algorithme glouton pour trouver de bonnes solutions n'ont jamais été proposés auparavant.

1.5 Plan du mémoire

Dans cette thèse, nous avons opté pour le format “par articles”. Certains chapitres sont donc la transcription d'articles publiés dans, ou soumis à, des revues scientifiques. Suite à ce chapitre d'introduction, le Chapitre 2 présente une revue critique et sélective de la littérature sur les problèmes clés du support de la QdS dans les RCMSF, et aussi, sur les mécanismes de déploiement de capteurs. Les différents algorithmes et mécanismes rencontrés dans la littérature nous ont permis de faire ressortir des problèmes et défis qui ont servi de base de recherche à cette thèse. Ensuite, le Chapitre 3 présente le premier article Cobo *et al.* (2010) intitulé *Ant-based routing for wireless multimedia sensor networks using multiple QoS metrics* et publié dans la revue *Computer Networks.* Dans cet article, nous proposons un protocole de routage basé sur la méta-heuristique de la colonie de fourmis qui permet trouver des routes pour le flots de données à partir des exigences de QdS spécifiées par la couche application et qui est adaptatif aux conditions courantes du réseau. Le Chapitre 4 présente notre deuxième article intitulé *A Distributed Connection Admission Control Strategy for Wireless Multimedia Sensor Networks*, qui a été soumis à la revue *Journal Of Communications And Networks.* Dans cet article, un nouvel algorithme réparti pour l'admission de flots multimédia à un RCMSF est proposé. L'algorithme est compatible avec n'importe quel type de protocole de la couche de réseau ou MAC et il est capable de réserver les ressources demandées par le flot s'il est accepté dans le réseau. Le Chapitre 5 présente notre troisième article intitulé *Integer Programming Formulation And Greedy Algorithm for 3-D Directional Sensor Placement in Wireless Multimedia Sensor Networks*, qui a été soumis à la revue *ACM Transactions on Sensor Networks (TOSN).* Nous y abordons le problème de déploiement optimal de capteurs directionnels et nous y présentons un modèle de planification ainsi qu'un algorithme glouton afin de trouver de bons résultats en un temps raisonnable.

Au Chapitre 6, une discussion générale présente les différents résultats obtenus ainsi qu'une synthèse de nos contributions scientifiques et nous concluons la présente thèse au Chapitre 7 en mettant l'accent sur les principales contributions apportées et en dégageant les principales limitations de nos travaux. Des recommandations pour des travaux futurs y sont également apportées.

CHAPITRE 2

REVUE DE LITTÉRATURE

2.1 Qualité de service pour les RCMSF

La gestion de la QdS pour les RCMSF reste encore un défi pour les chercheurs. Selon Almalkawi *et al.* (2010), il y a plusieurs problèmes à résoudre pour ce type de réseaux qui ne permettent leur vaste utilisation. Les problèmes que l'on doit tenir compte se trouvent dans les couches d'application, de transport, et de réseau (routage). On va présenter quelques solutions qui se trouvent dans la littérature traitant de tels sujets.

2.1.1 La couche application

Pour les auteurs de (Akyildiz *et al.*, 2007; Gurses et Akan, 2005), le contrôle d'admission offert par la couche application est un des problèmes à résoudre pour les RCMSF. Le contrôle d'admission, c'est-à-dire, le fait d'éviter aux applications d'établir des flots de données lorsque les ressources nécessitées du réseau ne sont pas disponibles, doit être basé sur les exigences de qualité de service de l'application sous-jacente. Selon Akyildiz *et al.* (2007), les RCMSF fourniront des services différenciés pour les différents types de paquets qui y circuleront. En particulier, ils devront fournir le service différencié entre les paquets de temps-réel et les paquets qui tolèrent des délais, ou entre les applications qui admettent les pertes de données et celles qui ne les admettent pas. En plus, il y a des applications qui demandent un flot continu de données multimédia par une période prolongée de temps (*multimedia streaming*), tandis qu'il y a d'autres applications qui peuvent demander des observations obtenues dans une période de temps plus courte (*snapshot multimedia content*).

Perillo et Heinzelman (2003) présentent un algorithme de contrôle d'admission de la couche d'applications dont l'objectif est de maximiser le temps de vie du réseau soumis à des demandes de l'application telles que la bande passante et la fiabilité. Dans (Boulis et Srivastava, 2004), une méthode de contrôle d'admission pour des applications est proposée. Les auteurs proposent des manières pour mesurer en temps réel la consommation d'énergie qu'une application utilise dans un nœud capteur. À partir de ces mesures, les auteurs présentent une politique de contrôle d'admission optimale qui tient compte de l'énergie ajoutée aux nœuds individuels par la nouvelle application. Bien que ces approches considèrent des éléments de qualité de services dans la couche d'applications, elles ne considèrent pas les conditions multiples de qualité de service (comme le délai, la fiabilité ou la consommation de l'énergie) appliquées simultanément, tel qu'il est exigé par les RCMSF. Par conséquent, il y a clairement une nécessité à établir des mécanismes et des critères pour gérer l'admission des flots multimédia conformément aux conditions de qualité de service souhaitées par la couche d'application.

2.1.2 La couche réseau

La couche réseau d'un RCMSF est la responsable du transport de données entre un nœud et le SINK, et constitue un élément important pour fournir de la qualité de service grâce aux raisons suivantes :

a) Cette couche est responsable de l'obtention de routes efficaces qui tiennent compte de la consommation de l'énergie, qui sont stables et qui satisferont des paramètres de qualité de service demandés par l'application.

b) Cette couche sert d'intermédiaire entre la couche MAC et la couche application pour l'échange de paramètres de performance entre elles.

En raison des exigences intensives de ressources qui ont les applications multimédia et de la basse disponibilité de telles ressources dans un RCMSF, le travail du protocole de routage est très compliqué. Aussi, tel que nous l'avons mentionné au-dessus, la couche réseau sert comme un intermédiaire entre l'application et la couche MAC de chaque nœud du réseau. En plus, la couche réseau a la connaissance des diverses caractéristiques des routes trouvées entre chaque nœud du réseau et le SINK. La couche MAC ne connaît que les caractéristiques de point à point entre les différents liens du réseau. Finalement, la couche application n'a pas d'information des conditions du réseau et n'a que de l'information de l'application. Cela est la raison pour laquelle, pour répondre à des exigences de QdS de la couche application, il faut que chacune des trois couches collaborent parmi elles. La couche réseau est l'unique que peut faire correspondre les paramètres de QdS que la couche application demande aux paramètres de performance de la couche MAC. De manière semblable, grâce à la rétroaction de la couche MAC à la couche application, cette dernière pourra réaliser des *ajustements* aux ses propres paramètres.

La qualité de service est une exigence typique pour les protocoles de la couche réseau qui transportent de l'information multimédia. Cependant, le support de la QdS dans les RCMSF est une tâche difficile. La raison est simple : les restrictions d'énergie, la puissance de calcul limitée et la basse capacité de la mémoire des nœuds capteurs. Malgré cela, il y a aussi plusieurs recherches dans la littérature de protocoles pour la couche réseau qui fournissent de la QdS et qui permettent le transport d'information multimédia. Ces protocoles, on va les diviser en trois catégories : basés sur IntServ, basés sur DiffServ et routage à multiples routes

(Bhuyan *et al.*, 2010).

Protocoles basés sur IntServ

Ces protocoles utilisent des réservations des ressources par flot de données. Dans (He *et al.*, 2003), les auteurs ont proposé un protocole routage dénommé *SPEED* qui supporte les communications en temps réel dans un réseau de capteurs et fournit des garanties de temps réel de façon *soft*. Le protocole *SPEED* utilise un schéma d'acheminement géographique non-déterministe et sans sauvegarder l'état (*Stateless Non-deterministic Geographic Forwarding*) comme le mécanisme primaire de routage. L'avantage du routage géographique est qu'il n'existe pas la nécessité d'établir de routes entre l'origine et le destinataire des messages. Pour *SPEED*, les nœuds du réseau doivent supporter une *vitesse maximale de transmission* pour chaque paquet admis. Le terme "vitesse de transmission" est défini par les auteurs comme le taux auquel le paquet avance le long de la ligne qui va de la source à la destination. De cette définition de vitesse on peut déduire que le délai de bout-en-bout dans le réseau est proportionnel à la distance entre la source et la destination. Si une application veut une vitesse plus grande que la vitesse maximale de transmission, elle ne serait pas admise au réseau. L'algorithme de routage calcule le délai de transmission pour un paquet en utilisant la distance de entre le nœud actuel et la destination du paquet, et la vitesse maximale de transmission. Ce schéma est similaire en esprit au modèle d'IntServ car la connexion n'est admise que dans le cas que le réseau puisse garantir de la supporter. Dans les circonstances où quelques liens de la route deviennent congestionnés et ils ne sont plus capables de supporter la vitesse maximale de transmission, le protocole a des mécanismes pour détourner le trafic vers d'autres routes. *SPEED* utilise la technique nommé *back-pressure re-routing* pour surmonter la dégradation dans la transmission des paquets due à la congestion du réseau. Cette technique évite que les paquets traversent des liens congestionnés, et de cette manière, la vitesse de transmission de paquets est maintenue. Un des inconvénients de *SPEED* est que le protocole n'a pas de schéma pour établir les priorités des paquets. De plus, chaque nœud ne peut que transmettre à une vitesse inférieure ou égale à la vitesse maximale pour laquelle le protocole a été configuré. Néanmoins, si le paquet a besoin d'une transmission à plus haute vitesse (par l'exemple, pour se récupérer des congestions dans les nœuds précédents), cela n'est pas possible, même si le réseau peut supporter telle vitesse.

Protocoles basés sur DiffServ

L'approche *DiffServ* est très populaire dans les réseaux de capteurs sans fils étant donné son extensibilité. Dans cette approche, les paquets qui vont être transmis sont classifiés par des niveaux de priorité différents. Chacun de ces niveaux présente différents garanties de temps, de bande passante, de gigue, etc. Chaque priorité représente une classe de trafic, et aussi, chaque paquet appartient à une de ces classes de service en fonction de ses besoins.

Le protocole SAR présenté par Sohrabi *et al.* (2000), appartient à cette catégorie. Il utilise le schéma de priorités constantes pour chaque paquet. Pour ce protocole, chaque paquet qui appartient à un flot donné, a une valeur constante de la priorité et cette valeur reste fixe tout le temps que le paquet traverse la route vers sa destination. SAR utilise une approche multi-route basée sur des tables de routage pour découvrir de différentes routes qui répondent aux exigences de QdS et de conservation de l'énergie dans le réseau de capteurs. Le nœud source sélectionne une route particulière parmi toutes les routes découvertes pour l'utiliser dans la transmission d'un flot donné. Cette sélection est faite en tenant compte des exigences de délai du flot et les intentions d'équilibrage de charge de la source. Les nœuds intermédiaires de la route choisie prennent en compte la priorité du paquet au moment de le transmettre. L'avantage de cette approche est sa capacité pour supporter des classes diverses de trafic pour les paquets. Toutefois, l'utilisation des tables dans la mémoire des capteurs pour réaliser le routage est son majeur inconvénient. En effet, cette table requiert une quantité significative de mémoire dans chaque nœud capteur et, évidemment, cette méthode n'est pas extensible aux réseaux assez grands. De même, le fait qu'un paquet ne peut jamais changer de priorité empêche que les nœuds réagissent à des changements inattendus dans le réseau.

Akkaya et Younis (2005a) proposent un protocole basé sur la QdS pour le trafic généré par une réseau de capteurs sans fils consistant en des capteurs d'images. Ce protocole utilise aussi un schéma de priorités constantes où tous les paquets qui vont être transmis en temps réel ont la même priorité. Le protocole travail avec le concept de « le coût d'un lien ». Tel coût est défini à partir de l'énergie résiduelle de chaque nœud, l'énergie consommé pendant la transmission, le taux d'erreurs et d'autres paramètres de la communication. Tout le trafic dans le système est divisé en deux classes : *best-effort* et temps réel. Dans chaque nœud, une file d'attente est utilisée pour stocker les paquets de chaque classe. Le protocole trouve plusieurs routes de la source à la destination en utilisant une version étendue de l'algorithme de Dijkstra. Ensuite, la source sélectionne une route qui satisfait les exigences du délai de bout-en-bout du paquet et après envoie le susdit paquet au prochaine nœud de la route. Chaque nœud intermédiaire classifie le paquet reçu dans les catégories de temps-réel out de *best-effort*. L'algorithme de répartition associé au protocole ne permet jamais le blocage des paquets *best-effort*. Le mérite de cet algorithme réside dans le fait qu'il garantit la transmission des paquets *best-effort* tout en maximisant le débit du trafic en temps réel. Le principal inconvénient de cette approche réside dans le manque de support pour multiples priorités du trafic en temps-réel. Dans une application multimédia, des paquets différents pourraient avoir des exigences de QdS différentes, et pour ces motifs, cette approche ne satisfait pas ce besoin. D'autre part, l'algorithme pour calculer des routes multiples a besoin d'une connaissance complète de la topologie du réseau dans chaque nœud, et pour cette raison, on peut affirmer que cette approche n'est pas évolutive (*scalable*).

Felemban *et al.* (2006) présentent un mécanisme pour la transmission de paquets nommé *Multi-path Multi-speed Routing Protocol (MMSPEED).* Ce protocole utilise des catégories différentes pour les paquets et ces catégories peuvent changer dans chaque nœud du réseau. *MMSPEED* fournit un schéma de garantie de la QdS en deux domaines notamment : la gestion du temps et la fiabilité. Par rapport à la fiabilité, elle est obtenue grâce à un routage multi-chemin avec un nombre de chemins dépendant du degré de fiabilité requis pour un paquet. Quant au temps, la transmission des paquets dans un délai spécifique est obtenu grâce à la capacité du réseau d'offrir différents vitesses pour les paquets (un mécanisme paraît à celui du protocole *SPEED* (He *et al.*, 2003)). Ce schéma emploie aussi un routage géo-localisé, avec des procédures de compensation dynamique de position puisque les nœuds intermédiaires font des décisions basés seulement sur leur information locale. En plus, les nœuds intermédiaires ont la capacité d'augmenter la vitesse de transmission d'un paquet dans le cas où le paquet ne puisse pas atteindre la destination avec sa vitesse actuelle. *MMSPEED* utilise toujours IEEE 802.11e comme sa couche MAC, et le protocole profite des mécanismes d'affectation de priorités qui est offert par 802.11. De cette façon, chaque vitesse correspond à une classe de priorité de la couche MAC.

Bien que *MMSPED* résout plusieurs aspects de la QdS pour le trafique multimédia dans un réseau de capteurs, il y en a d'autres, tels que l'agrégation des données ou la considération de l'énergie au moment de transmettre des messages dont le protocole ne s'occupe pas et qui sont relevant pour une architecture de communication multimédia.

D'autres approches

Il existe dans la littérature, d'autres schémas de routage qui ne peuvent pas être classifiés comme basés sur l'IntServ ou sur le DiffServ. Ces protocoles sont spéciaux et résolvent des problèmes très spécifiques de la communication multimédia dans les RCSF.

Chen *et al.* (2007a) présentent une solution intéressante au problème de la transmission de vidéo dans un réseau de capteurs. Les auteurs partent de l'hypothèse que dans le réseau il n'y a qu'un capteur de vidéo (CV), et que tous les autres capteurs font seulement une autre activité : celle de véhiculer le vidéo du CV à la station base (le SINK). En plus, chaque capteur connaît parfaitement sa position géographique, de telle façon que le protocole proposé (nommé le "routage géographique directionnel" ou *RGD*) utilise les positions des nœuds pour trouver la meilleure route vers la station base. Pour le protocole, la vidéo est d'abord codée en utilisant le standard H.26L, mais aucune raison n'est explicitée dans l'article sur les motifs ou les avantages de l'utilisation de telle codification. Le protocole a deux caractéristiques importantes qui font de lui une solution originale. La première caractéristique est l'utilisation de plusieurs routes pour envoyer le flot de vidéo. À partir d'un paramètre connu comme le `PathNum` (lequel indique le nombre de chemins qui seront formés pour envoyer les données), le capteur de vidéo détermine les angles dans lesquels il trouvera les nœuds qui achemineront les paquets. La figure 2.1 présente le schéma de construction de chemins du protocole *RGD*.

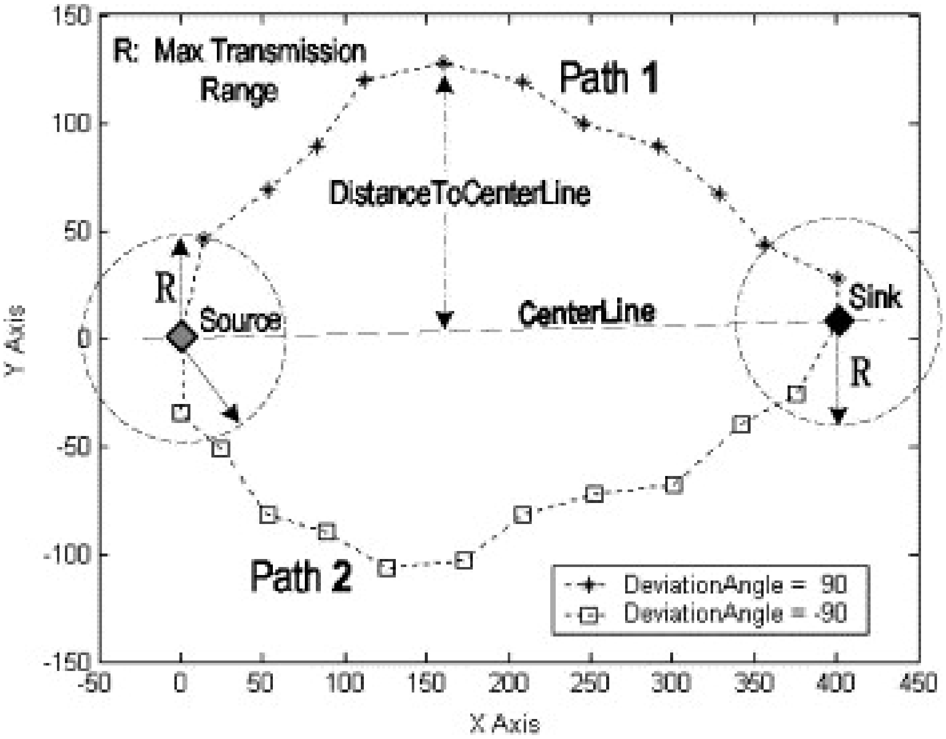

Figure 2.1 Exemple de routes formés par RGD avec *PathNum = 2*

Par chaque chemin, le capteur de vidéo envoie des sous-flots du flot de vidéo principal. Les sous-flots empruntent des routes différentes avec des nœuds non-partagés. Lors que le SINK reçoit les données, celui reconstruira la vidéo à partir de la fusion des paquets de chaque sous-flot. Les auteurs mentionnent que le routage multi-chemin permet d'augmenter la fiabilité de la transmission des données. Pour améliorer cette fiabilité, le protocole RGD transmet les paquets avec le code Forward Error Correction (FEC) pour permettre la correction, dans le SINK, des erreurs survenues au cours de la transmission sans besoin de retransmettre les paquets endommagés. Chaque sous-flot de n paquets envoyé par le capteur de vidéo consiste de k paquets d'une trame de la vidéo et n-k paquets redondantes qui sont générés pour protéger les k premiers paquets. Si le SINK reçoit k des n paquets, la trame de vidéo correspondante pourra être restaurée sans problèmes. En définitive, RGD offre un bon protocole pour la transmission de vidéo dans un réseau de capteurs. La combinaison de routage géographique, de multiples routes et du code FEC permet d'obtenir un protocole fiable et rapide, et ce, on peut le constater dans les résultats présentés dans l'article. Mais, les restrictions que ce protocole impose sont beaucoup : l'impossibilité d'avoir deux ou plus sources de vidéo, la spécialisation du réseau pour la transmission de vidéo (par exemple, les capteurs ne peuvent pas capter de données scalaires comme la température ou la lumière), la manque de considération de l'énergie des nœuds intermédiaires au moment de choisir les routes, la nécessite d'un grand nombre de capteurs intermédiaires qui permettent la création de plusieurs routes disjointes (sans nœuds en commun). Ces inconvénients nous révèlent que ce protocole est à une étape préliminaire et qu'il y a de travaux à faire pour l'améliorer.

Une autre approche, bien qu'il ne soit que pour le transport d'images, est présentée par Wu et Abouzeid (2006). Le protocole présenté dans cet article utilise un routage basé sur la formation des grappes dans le réseau de capteurs (*clusters*), et aussi sur l'utilisation de multiples routes dans une grappe et sur le traitement d'images dans le réseau (*in-network processing*). Quand la source souhaite transmettre une image vers le SINK, celle l'envoie d'abord à plusieurs nœuds dans la même grappe à laquelle appartient la source. Chaque nœud achemine l'image vers la tête de la prochaine grappe du réseau. Partant du fait que la source a envoyé l'image par différents chemins, c'est sure que la tête de grappe recevra plusieurs copies de la même image. Cela est l'avantage du protocole, puisque à partir de ces multiples images, la tête de grappe pourra choisir la meilleure ou simplement prendre de données de diverses images pour créer une bonne image de l'information reçue. Ce processus est appelé par les auteurs " *in-network diversity combining*" ou combinaison en diversité dans le réseau. En plus, les images sont envoyées en utilisant le schéma de protection d'erreurs FEC, que nous avons vu plus haut. En théorie, la combinaison de multiples routes avec le traitement dans le réseau et la redondance des données rend presque impossible la perte de l'information. Le routage continue à chaque tête de grappe. Celle fait le même processus que la source, c'est-à-dire, envoyer l'image à plusieurs nœuds dans la grappe, lesquels achemineront l'information vers la prochaine tête de grappe, et ainsi de suite, jusqu'à arriver au SINK. La figure 2.2 présenta un schéma de ce type de routage.

Les inconvénients principaux de ce protocole résident dans la spécialisation du réseau pour ne transmettre que des images, l'utilisation très grande de la mémoire des têtes de grappe pour recevoir et stocker tous les images qui proviennent des nœuds routeurs intermédiaires, l'impossibilité de que plusieurs sources d'images transmettent au même temps et la manque de critères de QdS pour choisir les routes. Néanmoins, il y a des concepts et des idées de ce protocole dont on peut profiter pour en construire un autre qui travaille d'une façon semblable

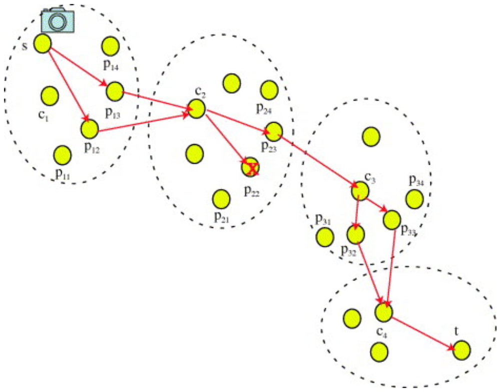

Figure 2.2 Schéma de routage du protocole présenté dans (Wu et Abouzeid, 2006)

mais pour la transmission de vidéo.

Routage pour ACO

Plusieurs solutions de routage pour réseau de capteurs sans fils utilisent le paradigme de colonies de fourmis présenté par Dorigo et Blum (2005). Mais la plupart parmi eux (par exemple (Camilo *et al.*, 2006; Chen *et al.*, 2007b; Sun *et al.*, 2008)) n'utilisent que l'énergie comme le paramètre de QdS pour trouver des routes. Dans les domaines des réseaux ad-hoc, on peut faire saillie les solutions proposées par Jeon et Kesidis (2005) et par Zheng *et al.* (2004). Les deux protocoles ont en commun l'utilisation de plusieurs métriques de QdS au moment de trouver des routes. Le protocole ADRA de Zheng *et al.* (2004) utilise le délai et la congestion des nœuds comme ses métriques, tandis que PPRA de Jeon et Kesidis (2005) utilise le délai et l'énergie des nœuds, mais pas ensemble, c'est-à-dire, l'application devra choisir de travailler avec une métrique ou avec l'autre. Mais, aucunes de ces solution ne tient compte les types de trafic diverses qui circulent dans le réseau.

2.2 Déploiement de capteurs directionnels

Les façons pour maintenir et optimiser la couverture d'une aire d'intérêt donnée ont été étudiées en profondeur dans les domaines du multimédia, la robotique et les réseaux de capteurs sans fil. Du point de vue du réseau de capteurs, un travail considérable est présenté pour le problème de couverture omnidirectionnelle (Cardei *et al.*, 2005; Gupta *et al.*, 2003; Tian et Georganas, 2002) qui vise à couvrir un ensemble de points critiques ou d'intérêts sur un plan en organisant des cercles avec chaque capteur déployé comme le centre du cercle. Toutefois, les solutions proposées pour une couverture omnidirectionnelle ne peut pas être utilisées pour le problème de la couverture avec des capteurs avec un champ de vision comme les caméras vidéo à basse résolution (capteurs de vidéo). Une limitation commune de ces solutions est que l'information collectée sur les phénomènes (par exemple, la température, la concentration d'une substance, l'intensité lumineuse, la pression, la humidité, etc.) est supposée provenant de n'importe quelle direction (détection omnidirectionnelle). Cependant, les capteurs multimédia, (c'est-à-dire, les caméras à basse résolution, microphones, etc.) ont la particularité de capter du contenu multimédia qui est sensibles à la direction. Surtout, les capteurs de vidéo seulement peuvent capturer des images utiles quand il y a une ligne de vue entre l'événement et le capteur (Akyildiz *et al.*, 2007). Ainsi, les modèles qui ont été élaborés pour la couverture traditionnelle dans les RCSF ne sont pas suffisants pour la planification du déploiement de capteurs multimédias dans un RCMSF.

Soro et Heinzelman (2005) traitent le problème de couverture pour les réseaux de capteurs vidéo. Le concept de la plage de détection des capteurs scalaires est remplacé par le champ de vue (FoV), qui est définie comme le volume maximum visible de la caméra lorsque les capteurs sont placés sur le plancher. Tous les nœuds sont supposés être situé sur un plan (le plafond de la salle de surveillance), et ils prennent les images de la scène à partir d'un plan parallèle. Un tel placement sur un plafond 2D, cependant, ne peut s'adapter qu'à applications spécifique. Toutefois, la solution proposé n'est pas optimal et elle est basée sur un schéma géométrique.

Une solution optimale au problème de déploiement de capteurs directionnels est présentée par Osais *et al.* (2010). L'article présente un modèle optimal pour le problème de minimiser le nombre de capteurs déployés sur un terrain 2D qui couvrent un ensemble de points d'intérêt. Mais, les auteurs se conforment avec le modèle mathématique qui nous donne la solution exacte au problème et ne proposent jamais une solution heuristique. En plus, la recherche est aussi limitée à capteurs déployés sur un plafond et cela le reste réalisme à la solution proposée.

Une solution pour le problème de déploiement de capteurs directionnels est présentée par Ma *et al.* (2009). Malheureusement, la solution n'est pas optimal et elle est aussi basée sur une méthode connue comme “les champs de potentielle virtuelle”. De cette façon, on peut conclure qu'il est nécessaire un méthode pour faire le déploiement optimal de capteurs directionnels dans un espace 3D.

CHAPITRE 3

ANT-BASED ROUTING FOR WIRELESS MULTIMEDIA SENSOR NETWORKS USING MULTIPLE QOS METRICS

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Abstract

In wireless sensor networks, most routing protocols consider energy savings as the main objective and assume data traffic with unconstrained delivery requirements to be a given. However, the introduction of video and imaging sensors unveils additional challenges. The transmission of video and imaging data requires both energy efficiency and QoS assurance (end-to-end delay and packet loss requirements), in order to ensure the efficient use of sensor resources as well as the integrity of the information collected. This paper presents a Quality of Service (QoS) routing model for Wireless Multimedia Sensor Network (WMSN). Moreover, based on the traditional ant-based algorithm, an ant-based multi-QoS routing metric (AntSensNet) is proposed. The AntSensNet protocol builds a hierarchical structure on the network before choosing suitable paths to meet various QoS requirements from different kinds of traffic, thus maximizing network utilization, while improving its performance. In addition, AntSensNet is able to use a efficient multipath video packet scheduling in order to get minimum video distortion transmission. Finally, extensive simulations are conducted to assess the effectiveness of this novel solution and a detailed discussion regarding the effects of different system parameters is provided. Compared to typical routing algorithms in sensor networks and the traditional ant-based algorithm, this new algorithm has better convergence and provides significantly better QoS for multiple types of services in WMSN.

Keywords : quality of service, routing protocols, wireless multimedia sensor networks, ant routing algorithm, video distortion.

3.1 Introduction

Rapid advances in Micro-Electro-Mechanical System (MEMS) technology, proliferation of wireless communication and digital electronics have set the stage for the deployment of low-cost, low-power, multi-functional, autonomous sensor networks. The major objectives behind the research and deployment of Wireless Sensor Network (WSN) (Akyildiz *et al.*, 2002) lie in the following two broad aspects : (i) Event detection (sensing) and data communication through node coordination and (ii) Conservation of energy to maximize the post-deployment, active lifetime of individual sensor nodes and the overall network. On the other hand, today's wireless communication is gradually changing the paradigms from the existing scalar services (light, temperature, etc.) to a new world of real-time audio-visual applications. The increasing popularity of multimedia applications has already given birth to the new term WMSN (Akyildiz *et al.*, 2007). Video surveillance, telemedicine, and traffic control will be the high-impact applications of emerging WMSNs.

The additional challenges created by the intrinsic features of multimedia communication must be addressed in order to deploy these multimedia applications within WMSNs. Unlike conventional data communication, required for reliable transport of event features from the field, multimedia traffic does not require 100% reliability, since it is endowed with most strict requirements on bounded delay, packet loss, minimum bandwidth, and smooth change of the transmission rate. These additional requirements inevitably amplify the challenges for multimedia communication in sensor networks. Especially, high bandwidth demands and strict multimedia communication time-constraints present significant challenges for sensor networks when matching energy and processing capacities with the level at which application objectives are met. While a significant amount of research has been conducted on WSN routing problems (Akkaya et Younis, 2005b), WSN multimedia data routing remains vastly unexplored. On the other hand, multimedia communication problems have been largely investigated and numerous solutions exist for wireless environments and the Internet. However, such solutions cannot be directly applied to WMSN scenarios due to their unique characteristics and resource constraints. Consequently, there is an urgent need for research efforts to address the challenges of WSN multimedia communications to help realize many currently envisioned multimedia WSN applications.

When network size scales up, routing becomes more challenging and critical. Lately, biologically-inspired intelligent algorithms have been deployed to tackle this problem (Chen *et al.*, 2007b; GhasemAghaei *et al.*, 2007; Muraleedharan et Osadciw, 2004; Zhang *et al.*, 2004; Liu *et al.*, 2007). Using ants, bees and other social swarms as models, software agents can be created to solve complex problems, such as traffic rerouting in busy telecommunication networks. Swarm intelligence, which is revealed by such natural biological swarms, offers various valuable properties renowned in many engineering systems, for instance in network routing. Swarm intelligence systems refer to complex behaviors, typically invented from some simple agents who cooperate with one another and their environment. One of the most successful swarm intelligence techniques is called Ant Colony Optimization (ACO) (Dorigo et Stützle, 2004), an optimization algorithm used to find approximate solutions for difficult combinatorial optimization problems. In ACO, artificial ants find solutions by moving on the problem graph, mimicking real ants who previously left behind pheromones for the use of future ants that can find better solutions. ACO was successfully applied to a remarkable number of optimization problems. Ants use reinforcement learning to discover the most efficient path. In reinforcement learning, the intelligent system is simply given a goal that must be reached. The system then adopts the goal using a trial and error interaction with the environment. Interactions that take the system close to the target receive a reward, while punishment is administered to those who stray away from the target. Computer scientists addressed reinforcement learning of artificial systems by introducing a concept called pheromone decay. When this pheromone evaporates rapidly, longer paths have trouble maintaining pheromone trails stable. This has also been used for telecommunication networks (Dorigo et Caro, 1998). Artificial ants continuously explore different paths, and pheromone trails to provide backup plans. Thus, if one link breaks down, a pool of alternatives already exists.

This paper proposes a QoS routing algorithm for WMSN based on an improved ant colony algorithm. The AntSensNet protocol introduces routing modeling with four QoS metrics associated with nodes or links. The algorithm can find a route in a WMSN that satisfies the QoS requirements of an application, while simultaneously reducing the consumption of constrained resources as much as possible. Moreover, by using clustering, it can avoid congestion after quickly judging the average queue length and solve convergence problems, which are typical in ACO. Simulation results show that the proposed algorithm improves the performance of other typical protocols such as Ad hoc On-Demand Distance Vector Routing (AODV).

The remainder of the paper is organized as follows : Section 3.2 provides a brief review of some closely related works. The proposed protocol is described in Section 3.3. Then, AntSensNet is tested through a series of computer simulations presented in Section 3.4. Concluding remarks appear in Section 3.5.

3.2 Related Work

As previously mentioned, WMSNs not only enhance existing sensor network applications such as tracking, home automation, and environmental monitoring, but they also enable several new applications such as multimedia surveillance sensor networks, automobile traffic management (traffic congestion avoidance systems, speed control, car parking assistance), storage of potentially relevant activities, advanced health care delivery, structural health monitoring, and industrial process control (visual inspection, automated actions). Many of these applications require the sensor network paradigm to be re-thought in view of the fact that, in these types of networks, the main concerns are not only energy constrains, limited computing power, and memory availability of the Sensor Nodes, but also the need for mechanisms to deliver multimedia content with a certain level of Quality of Service (QoS) : the transmission of imaging and video data requires careful handling in order to ensure that end-to-end delay remains within an acceptable range, while the delay variation is acceptable, the link bandwidth pertains to the tolerable compression ratio, that jitter is satisfactory and that there is a low packet loss rate (Akyildiz *et al.*, 2007).

Providing QoS guarantees in wireless sensor networks consists of a very challenging problem, but several approaches have been proposed in the literature for QoS support in these kinds of networks. For example, Sequential Assignment Routing (SAR) (Sohrabi *et al.*, 2000), one of the first approaches in the area of QoS for wireless sensor networks, builds multiple paths from a source node to the sink node. Path selection considers both QoS metrics (the flow delay requirements and the source load balancing intentions) and energy resources, to avoid nodes with low QoS and energy reserves. Intermediate nodes forward packets according to their level of priority. However, the algorithm does not consider reliability issues and it cannot scale large networks due to the use of a routing table to calculate multiples paths.

An energy-aware QoS routing protocol for real-time traffic generated by a wireless sensor network consisting of image sensors is proposed by Akkaya et Younis (2005a). This approach finds multiple network routes by using a minimum path cost. Such cost is a function of distance between nodes, node residual energy, energy transmission, and error rates which meet the requested end-to-end delay constraints. All traffic is divided into best effort and real time classes. A Weighted Fair Queuing (WFQ) approach is used at every node to provide the required share of bandwidth for both traffic classes. Path generation is performed in a centralized manner, at the base station using an extended version of Dijkstra's Algorithm. The advantage of this algorithm lies in the fact that it provides a guarantee for best-effort transmission, while simultaneously trying to maximize real-time traffic throughput. The main drawback is that the algorithm requires complete knowledge of the network topology at the base station to calculate multiple routes, thereby limiting the scalability of this approach.

The Real-time communication Architecture Protocol (RAP) proposed by Chenyang *et al.* (2002) uses a velocity monotonic scheduler to prioritize packets, and schedules them on the basis of their required transmission speed. Geographic routing is used to forward traffic towards its destination, while velocity-aware scheduling, either static (computed at the source, based on both deadline and distance to destination) or dynamic (computed at every node, based on the actual progress of the packet) ensures that packets meet their deadlines by giving higher priority to packets with higher requested velocities. However, when calculating routes, this protocol fails to consider energy issues and the number of hops executed by the packets.

A QoS routing protocol, called SPEED, was proposed by He *et al.* (2003) to provide a soft real-time end-to-end timeliness guarantee. The protocol requires that each node saves information regarding its neighbors and exploits geographic forwarding to find paths. In addition, SPEED strives to ensure a certain rapidity for each packet delivery so that each application can estimate the end-to-end delay for the packets by considering the distance to the sink and the speed of the packet delivery before making the admission decision. Using the distance and delay, each node evaluates the packet progress speed of each neighbor node and forwards a packet to a node whose progressive speed is higher than the pre-specified lower-bound speed. In the event that some path links become congested and cannot support the maximum delivery speed, the protocol includes mechanisms to divert traffic to other routes. One of the drawbacks of SPEED is that it does not have a packet prioritization scheme. In addition, the protocol does not provide any guarantee regarding packet reliability.

The QoS routing approach presented by Agrawal *et al.* (2006) utilizes the geographic location of sensor nodes as well. This protocol assigns an urgency factor to every packet depending on the remaining distance and the time left to deliver the packet. It determines the distance required for the packet to be sent closer to the destination in order to meet its deadline. Each node assigns a priority to all of its neighbors, according to their residual energy and delay, as well as the priority of the packets, and packets are forwarded to the highest priority nodes. Packets are sorted in two different queues, one for non-real-time traffic, and another one for real-time traffic. Real-time traffic is prioritized based on its urgency factor, scheduling those packets with more aggressive deadlines first for transmission. Reliability is achieved by using duplication of information at the source node. However, the protocol does not consider data aggregation and the network lacks a good decongestion scheme.

A multi-path and multi-speed routing protocol called “MMSPEED” is proposed by Felemban *et al.* (2006), which takes into account both timeliness and reliability as QoS requirements. The goal is to provide QoS support that allows packets to choose the most proper combination of service options depending on their timeliness and reliability requirements. For timeliness, multiple QoS levels are supported by providing multiple packet delivery speed guarantees. The scheme employs localized geographic forwarding with dynamic compensation to offset inaccuracies in decisions made with only local knowledge. Intermediate nodes have the ability to boost a packet's transmission speed to higher levels if they notice that the packet may not meet its delay deadline at the current speed, although the deadline could be met at a higher speed. MMSPEED assumes the use of IEEE 802.11e at the MAC layer with its inherent prioritization mechanism based on the Differentiated Inter-Frame Spacing (DIFS). Each speed value is mapped onto a MAC layer priority class. For reliability, multiple reliability requirements are supported by probabilistic multi-path routing with the number of paths being dependent upon the required degree of reliability. MMSPEED adapts to network dynamics such as channel error conditions and speed changes to determine the number of forwarding nodes (thus forming multiple paths) in each hop to satisfy the overall reliability and timeliness of QoS requirements. However, MMSPEED fails to consider energy issues ; hence, it is only applicable for short-term WSN applications whose mission lasts only a few hours or at most one day. Moreover, it does not handle network layer aggregation and requires substantial state information to be stored at intermediate sensor nodes.

Finally, ReInForM (Deb *et al.*, 2003) was proposed to address end-to-end reliability issues. ReInForM considers the importance of the data in the packet and it can adapt to channel errors. The protocol sends multiple copies of a packet along multiple paths from the source to the sink so that data can be delivered with the desired reliability. It uses the concept of dynamic packet state in the context of sensor networks to control the number of paths required for the desired reliability, based on local knowledge of the channel error rate and topology. However, the protocol only addresses QoS in terms of reliability, disregarding energy issues. In addition, the protocol does not consider route delays when selecting multiple paths.

The newly proposed solution to QoS routing in WMSNs is based on the ACO metaheuristic, especially due to the fact that the ACO algorithm (Dorigo et Blum, 2005) was inspired by the behavior of an authentic ant colony, more specifically real ants in a food search process. When ants are out searching for food, they leave their nest and walk toward the food. When an ant reaches a crossroad, it must decide which way to follow. While walking, ants deposit pheromones, leaving behind tracks of the route taken. Ants can smell pheromone and they are more likely to follow paths characterized by strong pheromone concentrations. The pheromone trails allow ants to find their way to the food source, or back to the nest. The same pheromone can be used by other ants to find the location of the food sources discovered by their mates. Based on this approach, there are many successful applications about the combinatorial optimization problems such as the Traveling Salesman Problem (TSP) (Dorigo et Gambardella, 1997), Vehicle Routing Problem (VRP) (Bullnheimer *et al.*, 1999) and routing algorithms in mobile ad hoc networks (Dorigo et Caro, 1998).

According to Rosati *et al.* (2007), a distributed heuristic solution such as ant routing displays several features making it particularly suitable in wireless sensor networks :

- the algorithm is fully distributed ; there is no single point of failure ;
- the operations to be performed in each node are very simple ;
- the algorithm is based on agents' asynchronous and autonomous interactions ;
- it is self-organizing, thus robust and fault tolerant ; there is no need to define path recovery algorithms ;
- it intrinsically adapts to traffic without requiring complex, and yet inflexible metrics ;
- it inherently adapts to all kinds of long-term variations in topology and traffic demand, which are difficult to take into account by deterministic approaches.

Additionally, ant routing has shown excellent performance to solve routing problems in WSNs and ad hoc networks. For instance, the Ant-Colony-Based Routing Algorithm (ARA) (Gunes *et al.*, 2002), suitable for MANETs, based both on *swarm intelligence* and ant-colony meta-heuristics, consists of three phases : route discovery, route maintenance and route-failure handling. In the route-discovery phase, new routes between nodes are discovered using forward and backward ants (FAs and BAs), similar to AntNet (Dorigo et Caro, 1998). Routes are maintained by subsequent data packets, i.e. as the data crosses the network, node pheromone values are modified so that their paths are *reinforced*. Also, same as in nature, pheromone values decay with time in the absence of such reinforcement. Routing or link failures, usually caused by node mobility, are detected through missing acknowledgments.

In (Gerla et Xu, 2003), a mobile ant-based routing protocol for large scale WSNs is proposed. Mobile ant nodes have greater capacity in terms of communication range length, high quality multimedia sensory data processing capability, mobility management, and better energy storage. The protocol defines three types of communication patterns : sensor to ant nodes, ant to ant nodes and ant nodes to the sink. Regular sensor nodes detect the events and report to the nearest ant node(s) and the mobile ant nodes relocate them nearest to the event hotspot to capture detailed multi-modal information about the event for more accuracy. The routing protocol maintains a hierarchy of clusters and uses two types of routing tables : for intra-cluster and inter-cluster routing. The protocol is intended for upstream routing and uses only a dedicated high bandwidth backbone channel to communicate with the sink and avoid congestion. The protocol does not evaluate multimedia metrics such as bandwidth, packet loss ratio, jitter, and end-to-end delay. Also, it does not actually employ ant-based routing phenomena.

A multi-path routing protocol based on ACO intended for Mobile Ad-hoc Networks (MANET) is proposed in (Ziane et Melou, 2005). The protocol specializes in carrying multimedia real-time traffic over the MANET. To provide higher bandwidth and delivery guarantees, it uses a multi-path solution. It also supports high mobility for nodes and certain QoS parameters. However, the protocol uses the concept of IP-based routing and must be modified in order to be suitable for WSN.

The M-IAR protocol proposed in (Rahman *et al.*, 2008) is a flat multi-hop routing protocol that exploits the geographic location of the sensor nodes in order to select the best route possible. Basically, M-IAR finds the shortest route, the one that contains the fewest nodes between the sending and receiving nodes. The authors believe that multimedia processing is costly for resource constrained sensor nodes, in addition to the wireless communication costs. Thus, finding the shortest path with the least number of forwarding nodes will help achieve the least end-to end delay along with the best jitter conditions. However, this protocol does not differentiate packets when selecting routes. Furthermore, it ignores the concept of packet priority. Moreover, the basic assumption that shorter routes equal best routes is erroneous, especially in WMSNs with heterogeneous nodes and different link bandwidths. Finally, this protocol is unable to handle link or node failures.

Another interesting protocol is TPGF (Two-Phase geographic Greedy Forwarding) proposed in (Shu *et al.*, 2010). TPGF takes into account both the requirements of real time multimedia transmission and the realistic characteristics of WMSNs. It finds one shortest (near-shortest) path per execution and can be executed repeatedly to find more on-demand shortest (near-shortest) node-disjoint routing paths. TPGF supports three features : (1) hole-bypassing, (2) the shortest path transmission, and (3) multipath transmission, at the same time. TPGF is a pure geographic greedy forwarding routing algorithm, which does not include the face routing, e.g., *right/left hand rules*, and does not use planarization algorithms, e.g., GG or RNG. This point allows more links to be available for TPGF to explore more routing paths, and enables TPGF to be different from many existing geographic routing algorithms. But this protocol presents some inconvenience when an application wants to transmit video between a source and the sink. TPGF only takes into account to create a route the “distance” between the nodes and the sink, and other important characteristics such as link bandwidth or node queue congestion, are not considered at the moment of route discovering. Besides that, this protocol does not support heterogeneous traffic (video and scalar data at the same time).

An ant-based protocol specifically designed for WMSN is ASAR (An ant-based service-aware routing algorithm for multimedia sensor networks) presentd in (Sun *et al.*, 2008). This protocol define three different types of services found in a sensor networks, namely, event-driven, data query and stream query services. The ASAR chooses suitable paths to meet diverse QoS requirements from different kinds of services, thus maximizing network utilization and improving network performance. Compared to the typical routing algorithm in sensor networks and the traditional ant-based algorithm, ASAR algorithm has better convergence and provides better QoS for multiple types of services in the multimedia sensor networks.

This protocol has important elements to take into account, but it lacks some others like multipath data transmission, a very important requirement in order to increase transmission performance in WMSNs.

As mentioned above, ant-based routing algorithms exhibit a number of interesting properties for WMSN routing. However, theses algorithms have a major drawback : scalability. This problem arises since each node must send agents (*ants*) to all other network nodes in order to discover a route to the sink, meaning that the total number of agents to be sent is $N \cdot (N-1)$. In large networks, the amount of traffic generated by the ants would be excessively high. Furthermore, nodes located far from the sink increase the probability of the ants getting lost. Moreover, the ants' extensive travel times contribute to outdating the information they carry. That is the main reason why it was decided to add a clustering mechanism to the algorithm, to ensure that the protocol is more scalable and efficient. Simulation results corroborate this decision. Therefore, WMSNs will henceforth be designed based on cluster-based architecture. Nodes in the cluster are responsible for collecting scalar and multimedia data before sending this information to the Cluster Head (CH). The CH fuses such data, and then transfers the data results upstream to the sink. The sink node manages the status of CHs and broadcasts signals to the WMSNs. CHs form an independent network. They connect the sink node via multi-hop wireless links. Therefore, this paper addresses mainly the routing scheme between the CHs and sink node.

None of the existing protocols can achieve all the following goals simultaneously :

- Traffic classification, in order to differentiate network data flows, and to treat each flow with its proper QoS metrics,
- Clustering, in order to solve the scalability problems in large-scale sensor networks and to facilitate in-network processing tasks (i.e. aggregation).

3.3 The AntSensNet Protocol

AntSensNet is a specially designed routing protocol for WMSNs. It combines a hierarchical structure of the network with the principles of ACO-based (Ant Colony Optimization) routing, thus satisfying the QoS requirements requested by the applications. Besides that, our protocol supports a power efficient multipath video packet scheduling scheme for minimum video distortion transmission

AntSensNet comprises both reactive and proactive components :

1. It is reactive since routes are set up when needed, not before. Once routes are set up, data packets are sent stochastically over the different paths using a pheromone table placed in each router.

2. It is proactive due to the fact that, while a data session is in progress, paths are probed, maintained, and improved proactively using a set of special agents designed for this task.

The algorithm comprises three parts. The first constituent clusters network nodes into colonies. The second component finds network routes between clusters that meet the requirements of each application in the network using ants. The third element forwards network traffic using the routes previously discovered by the ants.

3.3.1 WMSNs QoS Routing Model

A WMSN can be presented as a connected, undirected and weighted graph $G = (V, E)$ where $V = \{v_1, v_2, \ldots, v_n\}$ denotes the set of nodes (only CHs and sink node) in the network and $E = \{e_{12}, e_{13}, \ldots, e_{xy}\}$ depicts the set of bi-directional links between CHs. For a pair of nodes $v_i, v_j \in V (i \neq j)$, if the link $e_{ij} = (v_i, v_j) \in E$ then (v_i, v_j) consists of a pair of adjacent nodes. Each node $n \in V$ in the graph, includes a set of four QoS metrics elements : $\{pl(n), ma(n), dl(n), re(n)\}$. Where $pl(n)$ expresses the maximum packet loss rate of Node n, $ma(n)$ denotes the available memory in Node n, $dl(n)$ shows the queuing delay in Node n and $re(n)$ reveals the normalized remaining energy in the node n with respect to the initial energy, defined as : $re(n) = \frac{E_{residual}(n)}{E_{initial}(n)}$, where $E_{residual}(n)$ unveils the remaining energy in the battery of Node n and $E_{initial}(n)$ indicates the initial energy in the battery of Node n. These parameters, along with bandwidth, were chosen from those mentioned by (Akyildiz *et al.*, 2007), as important elements to find routes in a WMSN.

For a unicast path $P = (v_a, v_b, \ldots, S)$ from a CH v_a to the sink node s, its QoS parameters are computed as follows :

$$delay(P) = \sum_{n \in P} dl(n) \tag{3.1}$$

$$packetloss(P) = 1 - \prod_{n \in P} pl(n) \tag{3.2}$$

$$energy(P) = \min_{n \in P}\{re(n)\} \tag{3.3}$$

$$memory(P) = \min_{n \in P}\{ma(n)\} \tag{3.4}$$

In a WMSN, various kinds of traffic are transported by nodes. For instance, real-time audio/video data are delay-constrained with a certain bandwidth requirement. Packet losses can be tolerated to a certain extent. In addition, environmental data from scalar sensors, or non-time-critical snapshot multimedia content, are delay-tolerant and loss-tolerant kinds of data with low or moderate bandwidth demands. Finally, each type or *class* of traffic has its own requisites for QoS metrics. The goal of the AntSensNet algorithm is to find accessible paths for each *class* of traffic from a source CH node to the sink that meet different QoS requirements, thus minimizing interference among the types of traffic, balancing traffic distribution and improving network performance.

Let v_{ch} denote a CH and s denote the network sink node. The issue of routing selection from v_{ch} to s consists of finding different accessible paths P_C, where C represents each traffic class that the application being executed on the WMSN has defined. The objective function of a path P_C can be expressed as follows :

$$\begin{aligned} f(P_C) = {} & \gamma_C^d \cdot (D_{\max} - delay(P_C)) \\ & + \gamma_C^p \cdot (1 - packetloss(P_C)) \\ & + \gamma_C^p \cdot (energy(P_C) - E_{\min}) \\ & + \gamma_C^m \cdot (memory(P_C) - M_{\min}) \end{aligned} \tag{3.5}$$

where $delay(P)$, $packetloss(P)$, $energy(P)$, and $memory(P)$ respectively denote delay, packet loss rate, residual energy ratio and available memory for the path as defined in Equations (3.1) to (3.4). $D_{\max}$, $E_{\min}$ and $M_{\min}$ indicate the path's maximal tolerable delays, its minimal residual energy ratio and normalized memory available, respectively. Variables γ_C^d, γ_C^p, γ_C^p and γ_C^m translate the delay weight factor, packet loss rate, residual energy ratio and available memory for global QoS parameters, respectively.

The described QoS routing problem is similar to typical Path Constrained Path Optimization (PCPO) problems, which are proved to be NP-complete (Feng *et al.*, 2002), and an ant colony optimization based algorithm is used to solve this issue.

3.3.2 Assumptions

The following assumptions are made for this novel sensor network :

- Nodes are scattered randomly, in a uniform distribution, over a two-dimensional plane.
- The sink is not mobile and considered to be a powerful node endowed with enhanced communication and computation capabilities and no energy constraints.
- Sensor nodes are not mobile.
- There are two types of sensors : multimedia sensors (resource-rich nodes, capable of audio/video sensing of their environment) and scalar sensors that capture data such as temperature, light or pressure. Both types are also distributed randomly over the area.
- Nodes are unaware of their location, i.e. they are not equipped with a GPS device.
- Communication from each node follows an isotropic propagation model.

- Radio transmitting power is controllable, i.e. nodes can adjust the transmitting power according to the distance.
- Despite the fact that nodes are heterogeneous, it is assumed that radio transmissions are identical for all nodes.
- Nodes can estimate the approximate distance by the received signal strength, given the transmit power level is known, and the communication between nodes is not subject to multi-path fading.
- We use the same radio model presented in (Heinzelman *et al.*, 2002), and it is assumed that the radio channel is symmetric so that the energy required to transmit a m-bit message from Node i to Node j is identical to the energy required to transmit a m-bit message from Node j to Node i, for a given signal to noise ratio.

3.3.3 Clustering Process

AntSensNet is a QoS routing protocol based on an ant colony algorithm. This algorithm makes use of special agents (known as *forward-ants* or FANTs) to find a path between a sensor node and the network base-station or *sink*. In the route discovery process, several ants leave their node source, aiming for their neighbors, each one with the task of finding a route, meaning that sensor nodes must communicate with one another and the routing table of each node must contain the identification of all sensor nodes in the neighborhood as well as their corresponding levels of pheromone left on the trail. As the number of nodes grows, the number of agents required to establish the routing infrastructure may explode (Selvakennedy *et al.*, 2007). A way to overcome the overhead explosion and reach scalability consists of using the hierarchical routing approach.

Nevertheless, scalability is not the only reason to cluster the network. This process also allows for improving network data aggregation mechanisms, while concentrating this activity in the CH, consequently reducing node workloads, saving energy and increasing the network lifetime. Arboleda et Nasser (2006) presents other advantages of clustering that apply to this novel protocol : the fact that only the CH transmits information out of the cluster helps prevent collisions between the sensors inside the cluster, as they do not have to share communication channels with nodes in other clusters. This also promotes energy savings and avoids the black hole problem. Latency is also reduced. Although data must hop from one CH to another, they cover larger distances than when sensors use a multi-hop communication model (non-clustered) as the one used in other protocols.

Finally, clustering is applied in order to take advantage of the existence of nodes of different abilities inside a WMSN. Table 3.1 (Misra *et al.*, 2008) presents the processing performance and memory capacities among standard (TelosB) and multimedia sensors. Table 3.1 shows that the memory and processing capacities of multimedia sensors are superior to those of conventional sensors. That is the reason for selecting multimedia sensors to become the network CHs. This novel algorithm will be designed to favor the "selection" of these nodes as CHs.

Our clustering algorithm aims at achieving the following goals :

- Saving network resources by encouraging the selection of resource-rich nodes (multimedia sensor nodes) as network CHs.
- Ensuring network connectivity by forming a virtual backbone among the different CHs. Each CH is in the radio range transmission of at least one other CH. Communication between two CHs is direct (there are no relay nodes between them).
- Maximizing network lifetime by implementing a mechanism of CH rotation.

With a virtual backbone in the network, only CHs are concerned with data transportation, and other nodes are free to pursue their sensing tasks. Such task sharing improves network performance with respect to routing overhead and, moreover, a smaller number of nodes need to be alert for data transportation. This procedure reduces energy consumption, thus simultaneously maximizing network lifetime.

Information Update Phase

This novel clustering algorithm is based on T-ANT (Selvakennedy *et al.*, 2007) and the clustering protocol uses a collection of agents to form clusters in a sensor network. It is completely distributed and completed in constant time. These are the reasons why this algorithm was selected.

As in T-ANT, clustering operations are split into rounds. Each round comprises a cluster setup phase and a steady phase. In the steady phase of the algorithm, data transmission takes place between sensors and the sink. A number of timers are used to control the process operations. During the cluster setup phase, CHs are elected and clusters are placed around them. In order to avoid the maintenance of many state variables, as one finds in numerous current clustering proposals, a series of agents (known as *cluster-ants* or CANTS) are used to control CH elections. A node with a CANT becomes a CH, whereas others choose to join the best cluster in range.

The cluster radius $R_{cluster}$ is defined as a tunable parameter that determines the minimum distance between any two CH nodes in the network. The value of this parameter always remains inferior to the sensor communication radio range (called r). Before the cluster setup phase, an information update phase is carried out by the sensors. Each sensor node broadcasts a `HELLO` packet with information regarding its ID, its *clustering pheromone value* ($\Phi_c(n)$) and its *state* to its neighbors. When a `HELLO` packet arrives, the node stores such information in a

Tableau 3.1 Abilities Of Video And Standard Sensors

	Stargate	Samsung S3C44B0X	TelosB
Clock Frequency	200/300/400 Mhz	66 Mhz	8 Mhz
Architecture	32 bit RISC	16/32 bit RISC	16 bit RISC
Memory	64 MB SDRAM 32 MB Flash	256 MB	10 KB 1 MB Flash
Cache	32 KB data 32 KB instruction	8 KB	Data not available
Cost ($)	595	500	100

table, the *neighborhood* or the neighbor's information table. This table is then used to select clusters, to join a cluster and to route data packets.

The clustering pheromone value determines whether it is appropriate for this node to become a CH. For each node, this value is calculated using the following formula :

$$\Phi_c(n) = (ma(n))^a \cdot (re(n))^b \tag{3.6}$$

where $ma(n)$ denotes the available memory in the node, $re(n)$ is the residual ratio of the node's energy and a and b denote the importance of each component of the pheromone : a for the memory capacity and b for the energy component. Thus, the application determines which component is most important when selecting a CH, namely, memory or energy or both.

The state indicates if the node is a CH or a member of a cluster or neither. These `HELLO` packets are constantly broadcast by the nodes throughout their lifetime.

Ant Release Phase

After the information update phase, the sink releases a fixed number of ants (i.e. control messages) into the network. Assuming that the terrain is square, $M \times M$, the number of ants to be released is set at $\lceil \frac{M^2}{\pi d^2} \rceil$, where d depicts half of $R_{cluster}$. The latter formula also represents the number of clusters that make up the network. Attempts are made to obtain complete coverage of the area with this number of clusters, where every node belongs to a cluster and the CHs are disseminated throughout the terrain. Ants move about the network in a random fashion, as far as they can, respecting the limits imposed by their Time-To-Live (TTL) values. The TTL value equals the number of ants. Hence, an ant can visit a large number of candidate nodes to become a CH before they die. When the sink releases an ant, it chooses one of its neighbors randomly according to the following probability distribution function :

$$prob_c(j) = \frac{\Phi_c(j)}{\sum_{i \in N_s} \Phi_c(i)} \tag{3.7}$$

where $\Phi_c(j)$ denotes the clustering pheromone value sent by Node j, as defined in Equation (3.6), and N_s represents the set of all of the sink neighbors located at a distance of at least $R_{cluster}$. Before releasing the next cluster ant, the sink waits for a timer to expire (`CLUSTER_TIMER`). Although the timer expiration is set at a random value, it always remains proportional to the delay of sending an ant from a node to a neighbor. The objective of this timer is to ensure that the ants' subsequent transmissions do not self-interfere. Aside from that, when the sink selects a neighbor, the pheromone value of that node is artificially decreased, in order to avoid choosing the same set of nodes repeatedly.

Algorithm 1 presents the tasks performed by the sink in order to start the clustering process.

ALGORITHM 1: Tasks developed by the sink

```
$d \leftarrow \frac{R_{cluster}}{2}$;
repeat
    Use probability distribution function ($prob_c$) to choose a neighbor ($i$) ;
    Send a cluster ant to node $i$ with a $TTL = \lceil \frac{M^2}{\pi d^2} \rceil$ ;
    Wait until a CLUSTER_TIMER expires ;
until all ants are released;
```

When an ant arrives at a node, that node will execute the tasks depicted in Algorithm 2.

Algorithm 2 shows that, in order to become a CH, the selected node must have received a *cluster ant* from another CH (or the sink) located at a distance $R_{cluster}$ from it. $R_{cluster}$ was previously defined as the minimal distance between two CHs. Hence, at the moment of selecting the following neighbor, the node reads its neighbors' information table and selects, with probability $prob_c$, a node whose distance is a minimum of $R_{cluster}$ in a random manner. The reason why a CH elects the next CH is to create a virtual backbone between the various CHs, a direct communication strategy between them. This backbone will facilitate the task of routing accomplished by the protocol AntSensNet. When a node becomes a CH, it broadcasts an `ADV_CLUSTER` message to advise its neighborhood of its new condition. It also changes the value of field *state* of a `HELLO` package subsequently sent by the node. Once a regular node receives an `ADV_CLUSTER` message from a CH located at a distance below $R_{cluster}$, it stores the corresponding information that pertains to that CH. This information is later used to join a given cluster. Contrary to other proposals documented in the literature, this CH election approach has a very small constant time and a low level of complexity. An ant's TTL indicates the maximum number of hops that it can perform. The CH pulverizes an ant once its TTL

ALGORITHM 2: Tasks developed by the other nodes

```
if an ant arrives at node i then
    if node i is not a CH then
        if there is a CH in the radius $R_{cluster}$ then
            Pick a random CH neighbor ;
            Send the ant to it ;
        end
        else
            Store the ant;
            /* This node is a CH                                  */
            Broadcast a message ADV_CLUSTER to neighbors in range $R_{cluster}$ ;
        end
    end
    else if node i is a CH then
        Decrement the TTL of the ant ;
        if $TTL > 0$ then
            Pick a random neighbor according to the probability function $prob_c$ ;
            Send the cluster ant to it ;
        end
        else
            Destroy the ant ;
        end
    end
end
```

reaches the value zero. This situation shows the existence of a superfluous number of clusters in the network, and the cluster ant is destroyed in order to avoid the creation of new clusters that would hinder the network.

The actual clustering process happens once another timer expires. A regular node decides to join a cluster when its `JOIN_TIMER` expires. This node chooses the nearest cluster to join (from all of the `ADV_CLUSTER` packages it received) by sending a `JOIN` message with its ID. When a CH receives `JOIN` messages, it stores such information in order to subsequently select a cluster member as a new CH. If a regular node has never received an `ADV_CLUSTER` package from a CH, it starts a `JOIN_TIMER` once again and repeats the latter process until this timer expires. However, if in the process, it receives neither an `ADV_CLUSTER` message nor a `HELLO` package from a CH, the node uses the nearest neighboring cluster member as a “bridge” to reach its CH.

When a CH realizes that the node μ is three o more hops away from it, that CH selects the neighbor in the path to μ as a new CH. This new CH broadcasts an `ADV_CLUSTER` message in order to contact other CHs and initialize their pheromone tables. In that way, we can get a better CH distribution to cover the whole network area. This new CH selection may be done in any moment in the protocol execution.

The properties of the proposed clustering algorithm can be highlighted as follows :

1. The algorithm is completely distributed. A node locally decides to become a CH if an ant reaches it or joins a cluster.
2. Given the absence of looping statements as a function of node quantity, it is clear that the election process has an $O(1)$ time complexity.
3. The algorithm ensures the creation of a backbone among the CHs. As all CHs are connected, paths to a sink can be easily discovered.

Figure 3.1 shows an example of a sensor network clustering using our algorithm.

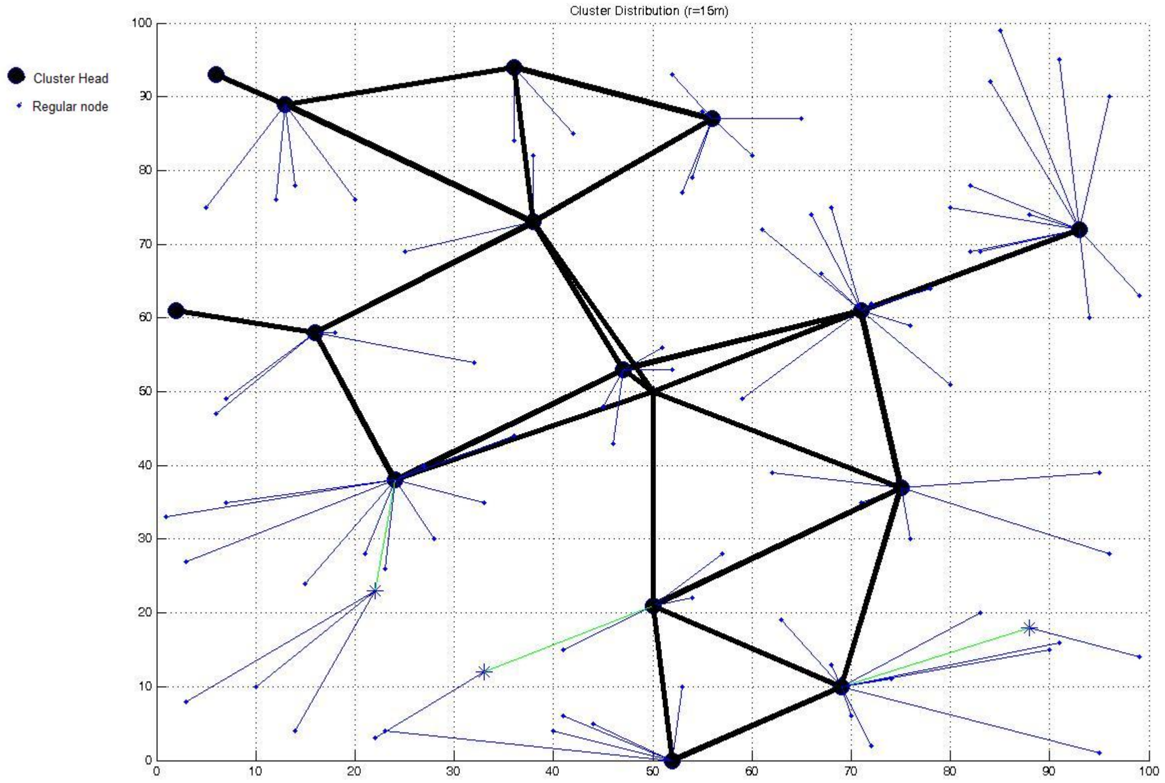

Figure 3.1 WMSN clustering example. The backbone created by CHs is outlined in black.

3.3.4 AntSensNet Algorithm Description

AntSensNet consists of a protocol based on ACO (Ant Colony Optimization) to discover and maintain routes between CHs and the sink. The route discovery process starts as soon as the cluster process finishes. Before presenting the algorithm, here are some definitions.

The Ant's Structure

The data configuration of the ant's structure used in its route discovery process is defined below. It comprises the following fields :

1. *ant.ID :* the ant's ID.
2. *ant.type :* the type of ant in the route discovery process. This field can be a Forward Ant (FANT), a Backward Ant (BANT), a MANT *(maintenance ant)* or a DANT *(data ant).*
3. *ant.nodes :* the nodes-visited-stack, contains the IDs of nodes by which the ant passes.
4. *ant.hopcount :* calculates the number of hops by which the ant passed from its CH source. This field serves as the ant's TTL.
5. *ant.info :* Each type of ant uses this field to store special information about the route or the nodes, in order to evaluate how appropriate the route is. This field contains the following subfields :
   - The minimum residual energy of the nodes by which the ant passed ;
   - The cumulative queue delay, packet loss, and available memory of each node visited by the ant.

The Queuing Model

Sensor data may originate from various types of sources whose levels of importance vary. Akyildiz *et al.* (2007) organizes the following examples of traffic into various WMSN classes :

- *Real-time, Loss-tolerant, Multimedia Streams.* This class includes video, audio or multilevel streams composed of video/audio and other scalar data (e.g., temperature readings), as well as metadata associated with the stream that need to reach a human or an automated operator in real-time, i.e., within strict time limits, although relatively loss tolerant (e.g., video streams can tolerate a certain level of distortion). Traffic that belongs to this class is usually associated with high bandwidth demands.
- *Delay-tolerant, Loss-tolerant, Multimedia Streams.* This class includes multimedia streams intended for storage or subsequent offline processing, whose delivery is not bound by strict delays. However, due to the typically high bandwidth demands of multimedia

streams and due to limited buffers of multimedia sensors, data that belong to this category need to be transmitted virtually in real-time in order to avoid excessive losses.

– *Delay-tolerant, Loss-intolerant, Data.* This may include data from critical monitoring processes, with low or moderate bandwidth demands that require some form of offline post processing.
– *Delay-tolerant, Loss-tolerant, Data.* This may include environmental data from scalar sensor networks, or non-time-critical snapshot multimedia content, with low or moderate bandwidth demand.

Hence, packet scheduling policy should consider different priorities (importance) for different types of traffic classes. Figure 3.2 shows the queuing model for a sensor considering different traffic classes. At the outset, the application must define these classes and their parameters, i.e. minimal energy, bandwidth, available memory and packet delays, and maximum packet loss. The application, rather than the protocol, is responsible for predefining the number of classes. The application is also responsible for assigning the class and priority of every packet sent by the sensors. For each CH, a classifier checks the class of the incoming packets which are then sent to the appropriate queues, and a scheduler organizes packets according to their classes and level of priority.

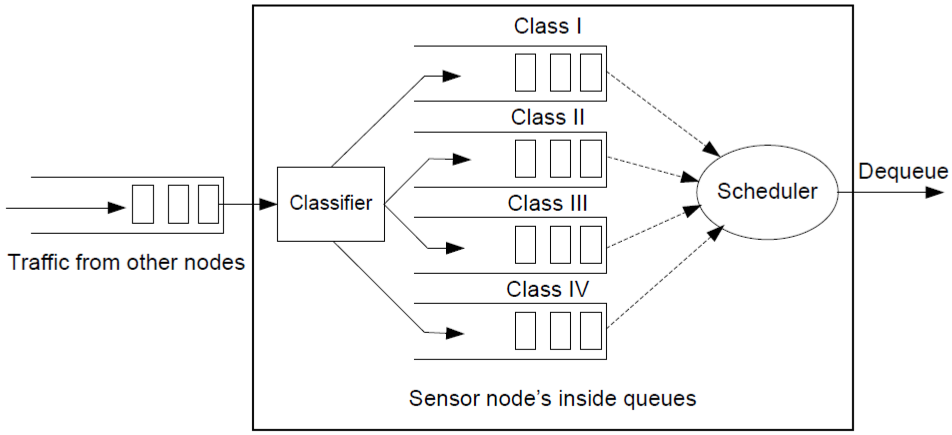

Figure 3.2 Queuing model on a multimedia sensor node

The fact that an application can define the classes of data for the queue enables a great flexibility but it should be used with caution. This characteristic would create problems when the application defines too many classes of traffic, it will degrade the performance of the nodes because of big utilization of memory

Pheromone Table

An ant pheromone table is a data structure that stores pheromone trail information for routing from Node i to the sink via a CH neighbor j. Saved into the node memory, this structure is organized as shown in Table 3.2 below.

Tableau 3.2 Pheromone table for Node i

Neighbor	**Traffic Class** k				**Class** t	**Expiration Time**
N_1	$e_i^k(1)$	$\delta_i^k(1)$	$\varepsilon_i^k(1)$	$\mu_i^k(1)$	$\cdots$	T_1
N_2	$e_i^k(2)$	$\delta_i^k(2)$	$\varepsilon_i^k(2)$	$\mu_i^k(2)$	$\cdots$	T_2
$\vdots$	$\cdots$				$\vdots$	$\vdots$
N_j	$\cdots$				$\vdots$	$\vdots$

In the table 3.2, each column reflects the different traffic class, as defined by the application. Each row corresponds to a neighbor. There are fivefour values for each traffic class in the table. Each value is a pheromone trail concentration for each QoS metric used by the protocol :

1. $e_i^k(j)$: energy pheromone value from link between Nodes i and j for packets that belong to traffic class k ;
2. $\delta_i^k(j)$: delay pheromone value from link between Nodes i and j for packets that belong to traffic class k ;
3. $\varepsilon_i^k(j)$: packet loss pheromone value ;
4. $\mu_i^k(j)$: available memory pheromone value.

Every entry in the pheromone table has an expiration time and certain entries are disabled as time goes on. When the current time exceeds the set expired time, a new route discovery phase commences.

Route Discovery

When a regular node needs to send data to the sink, such information is immediately sent to its CH. The working process of the AntSensNet algorithm is described as follows : when a CH node is in possession of sensor data to be sent, it checks its routing table to find an appropriate path for the traffic class of the packet. Before initiating a data transmission, the CH source checks out its pheromone table in order to find any non-expired node information. That information is expired if the value associated to the *Expiration Time* field is inferior to the node clock. If all the information in the pheromone table is expired, a new route probe phase is started. There are a number of forward ants needed to send for route probes. After the routing discovery process, cached data are immediately sent to their destination. To reduce delays associated with the first discovery phase, an AntSensNet algorithm launches a full route probe phase for each traffic class after the clustering process was ended. A packet flow that shows a CH receiving an ant is illustrated in Figure 3.3. There are three phases to the AntSensNet : the forward ant phase, the backward ant phase and the route maintenance phase.

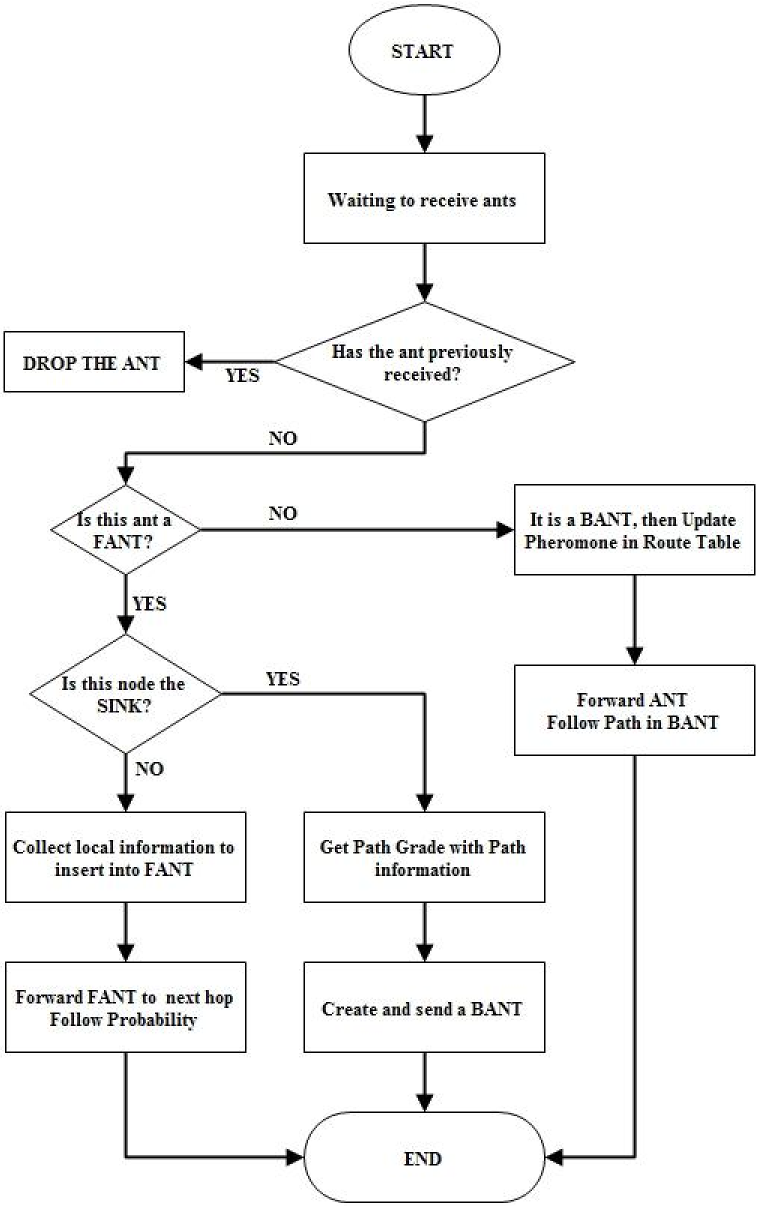

Figure 3.3 Route Discovery Process of AntSensNet

Forward Ants Phase : If a CH finds that there is no satisfactory and unexpired path to the sink in the packet's traffic class in its routing table, it generates a certain number of Forward Ants (FANTS) to search for paths leading to the sink. Forward ants are agents that establish the pheromone track from the source CH to the sink node. The ants' structure is presented above. In their info field FANTs carry :

- The minimum residual energy (*energy*) of the nodes by which the ant passed ;
- The cumulative queue delay (*delay*), packet loss (*packetloss*) and available memory (*memory*) of each node the ant visited.

These values are the QoS metrics used in order to discover routes. To find a route to the sink, the CH source broadcasts a FANT. Each field of the ant packet must be set before being sent, i.e., the type field $ant.type \leftarrow FANT$, $ant.hopcount \leftarrow 0$, and it pushes the CH source into the *ant.nodes* stack. When an intermediate CH receives a FANT, it judges the existence of loops on the *ant.nodes* field of the received FANT. Those ants resulting in route loops are discarded. Before sending the FANT to the next CH, the field $ant.info$ must be updated with local information regarding the current CH. This update is carried out in the following way :

ALGORITHM 3: Update process of a FANT

```
$energy \leftarrow \min(energy, re(CH))$ ;
$delay \leftarrow delay + dl(CH)$ ;
$packetloss \leftarrow packetloss \times pl(CH)$ ;
$memory \leftarrow \min(memory, ma(CH))$ ;
```

When a CH receives a FANT, it updates the info field of the ant, increments the ant's hop count and push its identification (e.g. i) on the ant's node stack. The next hop is selected according a certain probability value. The probabilistic value $P_i^k(j)$ determines the probability of moving from CH i to j for the traffic class k, which is computed as expressed by Equation (3.8) :

$$P_i^k(j) = \begin{cases} \frac{\Psi_i^k(j)}{\sum_{s \notin V_{pass}} \Psi_i^k(s)} & \text{if } j \notin V_{pass}, \\ 0 & \text{if } j \in V_{pass}. \end{cases} \tag{3.8}$$

where V_{pass} is the set of nodes that the FANT has passed. $\Psi_i^k(j)$ is the normalized value of pheromone from i to j for the traffic class k. This value combines all of the QoS parameters the application has established for the traffic class. In order to compute this value, the following probability value must be calculated :

1. The normalized energy probability :

   $$p^k_{e,i}(j) = \frac{e^k_i(j)}{\sum_{s \in N_i} e^k_i(s)}$$

   where N_i indicates the set of CH neighbors of CH i and $e^k_i(j)$ is the energy value for Node j and traffic class k in the pheromone table of Node i.

2. The normalized delay probability :

   $$p^k_{\delta,i}(j) = \frac{\delta^k_i(j)}{\sum_{s \in N_i} \delta^k_i(s)}$$

   where N_i denotes the set of CH neighbors of CH i and $\delta^k_i(j)$ depicts the delay value for Node j and traffic class k in the pheromone table of Node i.

3. The normalized packet loss probability :

   $$p^k_{\varepsilon,i}(j) = \frac{\varepsilon^k_i(j)}{\sum_{s \in N_i} \varepsilon^k_i(s)}$$

   where N_i identifies the set of CH neighbors of CH i and $\varepsilon^k_i(j)$ is the packet loss value for Node j and traffic class k in the pheromone table of Node i.

4. The normalized available memory probability :

   $$p^k_{\mu,i}(j) = \frac{\mu^k_i(j)}{\sum_{s \in N_i} \mu^k_i(s)}$$

   where N_i translates the set of CH neighbors of CH i and $\mu^k_i(j)$ is the memory value for Node j and traffic class k in the pheromone table of Node i.

Finally, the normalized pheromone value from i to j for the traffic class k, $\Psi^k_i(j)$, is calculated as :

$$\Psi^k_i(j) = \frac{\alpha_e p^k_{e,i}(j) + \alpha_\delta p^k_{\delta,i}(j) + \alpha_\varepsilon p^k_{\varepsilon,i}(j) + \alpha_\mu p^k_{\mu,i}(j)}{\sum_{s \in N_i}[\alpha_e p^k_{e,i}(s) + \alpha_\delta p^k_{\delta,i}(s) + \alpha_\varepsilon p^k_{\varepsilon,i}(s) + \alpha_\mu p^k_{\mu,i}(s)]} \tag{3.9}$$

Note that Ψ is calculated as the addition of all QoS parameters collected by the ants, that is, the energy, delay, bandwidth, packet loss and available memory pheromones, normalized into a single quantity with a comparable magnitude. Normalizing pheromones makes it possible to convert them into the same dimension. Note that *alpha* values are arbitrary, positive constants, which represent the importance of each QoS components in the selection of the next hop in the route.

Backward Ants Phase : When a forward ant reaches the sink, the evaluation of the found route is carried out. The information collected by the FANT is compared with the parameter values set by the application for each QoS metric. For instance, the application can demand routes with a packet-loss value that is inferior to 1% and a residual energy ratio superior to 80%. The sink evaluates the FANT's info versus these parameters and determines whether the route is adequate. If the route does not fulfill the application requirements, the FANT is discarded. The application must tune these parameters in order to obtain efficient routes. The sink may reject all of the paths found by the ants if parameters are unreal or impossible to obtain under the current network conditions.

When an appropriate FANT is received that meets the application requirements, the sink pulverizes the FANT and a BANT is generated. A BANT carries the collected information of its corresponding FANT and the path's intermediate node IDs and it is sent back using the reverse path of its corresponding FANT. When a BANT is received at intermediate CH i, the information stored inside such BANT is used to update the pheromone value and hence the probability routing table entry corresponds to the FANT's destination. The pheromone values on the incoming link are increased and the values pertaining to the other links are decreased using the pheromone update functions. These functions work as follows :

1. For the energy pheromone :

$$e_i^k(j) = \begin{cases} \rho_e \cdot energy + (1-\rho_e) \cdot e_i^k(j) & \text{incoming link} \\ (1-\rho_e) \cdot e_i^k(j) & \text{other links} \end{cases} \tag{3.10}$$

   where $e_i^k(j)$ depicts the pheromone value corresponding to residual energy for the traffic class k and Neighbor j at Node i, *energy* is the collected value by the corresponding FANT about the minimal path's residual energy and $\rho_e (0 < \rho_e < 1)$ is the pheromone improvement parameter for the incoming link. Its purpose is to enforce efficient routes while decreasing the appropriateness of the bad ones (pheromone evaporation). Other pheromone update functions are similar.

2. For the delay pheromone :

$$\delta_i^k(j) = \begin{cases} \frac{\rho_\delta}{delay} + (1-\rho_\delta) \cdot \delta_i^k(j) & \text{incoming link} \\ (1-\rho_\delta) \cdot \delta_i^k(j) & \text{other links} \end{cases}$$

   where $\delta_i^k(j)$ denotes the delay pheromone value stored in the CH i for Class k and Neighbor j, and *delay* represents the delay value collected by the corresponding FANT. Likewise, in the energy pheromone formula, $\rho_\delta (0 < \rho_\delta < 1)$ represents the pheromone improvement factor for the incoming link of the BANT and $(1-\rho_\delta)$ represents the pheromone evaporation factor for the others links.

3. For the packet loss pheromone :

$$\varepsilon_i^k(j) = \begin{cases} \frac{\rho_\varepsilon}{packetloss} + (1-\rho_\varepsilon) \cdot \varepsilon_i^k(j) & \text{incoming link} \\ (1-\rho_\varepsilon) \cdot \varepsilon_i^k(j) & \text{other links} \end{cases} \tag{3.11}$$

   where $\varepsilon_i^k(j)$ shows the packet loss pheromone value stored in the CH i for Class k and Neighbor j, and *packetloss* represents the packet loss value collected by the corresponding FANT. Similar to the delay pheromone formula,$\rho_\varepsilon (0 < \rho_\varepsilon < 1)$ represents the pheromone improvement factor for the incoming link of the BANT and $(1-\rho_\varepsilon)$ represents the pheromone evaporation factor for the others links.

4. Finally, for the available memory pheromone :

$$\mu_i^k(j) = \begin{cases} \rho_\mu \cdot memory + (1-\rho_\mu) \cdot \mu_i^k(j) & \text{incoming link} \\ (1-\rho_\mu) \cdot \mu_i^k(j) & \text{other links} \end{cases}$$

   where $\mu_i^k(j)$ indicates the memory pheromone value stored in the CH i for Class k and Neighbor j, and *memory* represents the packet loss value collected by the corresponding FANT. Similar to the delay pheromone formula, $\rho_\mu (0 < \rho_\mu < 1)$ represents the pheromone improvement factor for the incoming link of the BANT and $(1-\rho_\mu)$ expresses the pheromone evaporation factor for the others links.

The pheromone trails of the best route offer incentives, by providing a greater amount of pheromone. Furthermore, in the current of history, the worst route offers a pheromone punishment incite other ants to stay away from the worst solution.

The BANT is sent to the next CH in the reverse path of the corresponding FANT. When the BANT reaches the FANT's source CH, it is pulverized after updating the pheromone table of the source table. Data can then be sent to the sink following the maximum probability path.

Routing Maintenance Phase : While a node sends information that belongs to a given traffic class, FANTs are generated periodically in order to find updated routes, i.e. topology changes in the network that fulfill the QoS requirements specified by the application. The process of routing maintenance also deals with congestion and lost link problems.

1. *The Congestion Problem :* When the load of a queue of a traffic class at an intermediate CH surpasses a predefined threshold (called Γ), the CH sends a congestion-control MANT to its upstream neighbor nodes to modify the pheromone tables for the given

traffic class. The TTL of this MANT is set according to the severity level of the traffic : the heavier the traffic, the higher the TTL value. Upon receiving the MANT from the CH j, Node i reduces the strength of pheromone on the corresponding route and traffic class. Then, Node i uses other routes with a relatively high level of pheromone to forward packets that are part of the congested traffic class.

2. *The Lost Link Problem :* AntSensNet also uses periodic `HELLO` messages to update information about the connectivity of neighboring nodes. Once the next hop becomes unreachable, the CH first deletes all the entries, in the pheromone table of Node i, which correspond to the broken link, and then searches its pheromone table for an alternative neighbor node for subsequent data transmissions. The CH then sends a MANT to all neighbors in order to inform them that Node i is unreachable and that it must be removed from their pheromone tables.

Data Transmission Phase : In AntSensNet, a CH forwards data following the maximum pheromone value path. When a node has multiple next hops for a given traffic Class k, it selects one with the maximum Ψ. This value is calculated in the same way as that of a FANT, Equation (3.9). This strategy leads to data loading spreads according to the estimated path quality. When estimates are kept up-to-date, which is done by using the FANT, as described in the previous section, *automatic load balancing* ensues. When a path is clearly worse than another, it is avoided, thus reducing its traffic load. Other paths thus obtain more traffic, causing greater congestion, thus reducing their QoS parameters. Continuously adapting data traffic incites nodes to spread data loads evenly over the network.

Data Ants or DANTs : In AntSensNet, ants are special agents that assist in route discovery and maintenance. However, they are also high priority packets. They are sent, processed, and received by the CH with a higher priority than any other traffic class. A special ant, known as DANT (Data Ant), is assigned to transport urgent (or real-time) data from a node to the sink. In this case, the information is encapsulated in this special type of ant, and it is processed before all of the other traffic classes in every node. The behavior of DANTs is similar to that of FANTs, yet the former do not collect information from each CH they meet along their route, nor do they generate BANTs when they arrive at the sink. Also, they choose their next hop according to the path that has the maximum level of pheromones.

Video Transmission

If an application needs more accuracy to transmit video, AntSensNet offers a mechanism to transport a video stream between a source node and the sink. This mechanism use an efficient multipath video packet scheduling scheme for minimum video distortion over the wireless network. The mechanism is based on the “Baseline” algorithm proposed in (Politis *et al.*, 2008). That scheme uses H.264/AVC codec as encoding technique because of its compression efficiency, low complexity and error resiliency.

In that paper, the authors express that the high end-to-end bandwidth requirements of video communication usually can not be met by the WMSNs, when the traditional single path routing approach is used, leading to perceived video quality degradation. In order to meet the QoS requirements, a multipath approach should be adopted, where the video source delivers the data to its destinations via multiple paths, thereby supporting an aggregated transfer rate higher than what is possible with any one path. Specifically, the encoded video data are segmented and multiplexed in a specific way, based on their distortion importance, over different paths so that the sink can assemble the video data and decode them with the maximum perceived quality. AntSensNet, on an application demand, is able to create multiple paths to transport video packages. In other words, the protocol has the possibility to send the video packets using a single-path or a multi-path scheme, based on an application decision.

Multiple paths to the sink Multipath video transmission has been studied extensively (Golubchik *et al.*, 2002). The benefits of selecting multiple paths among a video server and a client instead of just the shortest path include among others :

- reduced correlation among packet losses
- increased channel resources that can support the application’s demands in QoS
- the power consumption is more evenly spread in the network nodes preventing node failures
- ability to adjust to arbitrary congestion occurrences in different parts of the network

When a video source wants to initiate a video transmission and its CH does not have an active route to the sink, that CH source initiates route discovery by broadcasting a special video forward ant (VFANT) packet to the CH neighbors. The behavior in each intermediate node is the same as when discovering a single-path. Unlike to the single-path routing algorithm, in order to discover multiple paths, intermediate nodes do not discard duplicate VFANTs. When a VFANT reaches the sink, it generates a video backward ant (VBANT) packet for the CH source node. The VBANT returns to the source using the nodes that corresponding VFANT visited. The routing table update methods are the same as single-path discovery. Since duplicate VFANTs are not discarded, the sink node may send multiple VBANTs back to the source. At the source, received VBANTs are examined and those that do not provide link-disjointness with the routes discovered by other VBANTs are discarded. After that, the CH source has a set of link-disjoint paths to use in a video transmission. When the video packet sending starts, the next hop is determined by the discovered routes and these routes are only modified when problems like congestion, like failures, etc., emerge.

Video Distortion Model We use the Baseline schedule algorithm proposed in (Politis *et al.*, 2008). This algorithm firstly identifies the possible paths from the CH sender to the sink that can on aggregate satisfy the quality of services requirements of the video service. Secondly, in case that the aggregate bandwidth of the multiple paths is limited, the algorithm utilizes the following video distortion prediction model to determine the least important packets that could be dropped prior to transmission.

In order to analytically express the distortion model, a list of previously encoded reference frames with size M_{REF} that is used during the encoding and decoding processes for motion-compensated prediction, is defined. This parameter accounts for the impact of the number of reference frames on the distortion propagation. Moreover, each frame is coded into a number of video packets according to each size. Finally, a simple error concealment mechanism, which replaces a lost frame with its previous at the decoder, is applied. The proposed model includes analytical models for a single frame loss, a burst of losses with variable burst length B (where $B \geq 2$) and frame losses separated by a lag.

Baseline packet scheduling Politis *et al.* (2008) introduce the "Baseline" packet scheduling algorithm. In our implementation, this algorithm use AntSensNet in order to transport the packages between a CH and the sink. Under these conditions the "Baseline" packet scheduling algorithm schedules the transmission of video packets via multi paths by dropping the excess video traffic in order to prevent network congestion.

In more details, channel resources in a WMSN are scarce and there are cases when the transmission requirements exceed the available aggregate transfer rate of the multiple paths. If the required rate for error free transmission (RTR) is higher than the current available aggregate transmission rate (ATR) then the sender decides which video packets will be optimally dropped in order to adapt its current rate to the allocated one. The packets to be dropped are selected according to their impact to the overall video distortion. A combination of one or more video packets may be omitted prior to the video transmission by the video source. Dropping a packet imposes a distortion that affects not only the current video frame but all the correlated video frames. The intelligence of the packet scheduling algorithm is that utilizes the distortion prediction model presented previously, which considers the correlation among the reference frames, thus it selects the optimum pattern of packets to drop in each transmission window.

This process is neither time nor power consuming, as the transmission window is generally small and the mathematical calculations are not of high complexity. The transmitted packets are distributed among the available routes according to their impact in the video distortion; hence packets of high importance are transmitted through the higher capacity routes.

3.4 Experimental Results

Three main aspects of AntSensNet were evaluated : its clustering process, its routing algorithm, and the video transmission mechanism, which were analyzed separately. In each instance, an NS-2 (VINT, 2008) was used to implement and simulate the novel algorithms. There are two types of nodes : scalars and multimedia (with more energy and memory than scalar nodes). Half of the nodes are multimedia. The radio range of the nodes spans 100 meters and the data rate equals 2 Mbit/s. At the MAC layer, a modified version of 802.11b DCF protocol was used. The modification was made in the queue politics of the MAC protocol in order to accept multi-class and multi-priority traffic.

3.4.1 The Clustering Process

For these simulations, it was assumed that 100 sensor nodes were distributed randomly over a square area of 100 m × 100 m. This scenario was executed during 600 seconds. In order to benchmark this new protocol, it was decided to compare it to T-ANT (Selvakennedy *et al.*, 2007), as it was the base of our clustering protocol and also since it outperformed other well-known clustering algorithms, such as LEACH (Heinzelman *et al.*, 2002) and HEED (Younis et Fahmy, 2004). For this experiment, an $R_{cluster} = 20m$ is assumed, and the same CH rotation scheme is used in AntSensNet as in T-ANT : there are multiple rounds in the network lifetime, and in each round, a CH rotation is carried out. The CH finds its cluster member whose level of pheromone, Equation (3.6), is the highest, before it becomes the CH for the next round.

Figure 3.4 depicts the CH connectivity of these protocols at different simulation time. This property indicates if there is direct communication between the CHs of the network, meaning that no CH isolated. This property is very important in this novel algorithm, as all of the traffic between source nodes and the sink is transported by the CH. If CHs are isolated, it is impossible to transmit information from that cluster to the sink. In this simulation, any node can be a CH, in other words we set $a = b = 0$ in Equation (3.6). Observe that after only 20 rounds, (one round $20s$ each), the connectivity of T-ANT is acceptable. Meanwhile, the connectivity of AntSensNet remains at a steady 100%. The main design goal of our clustering algorithm is reached with the permanent connectivity of the CHs.

In Figure 3.5, the improvement gained through our AntSensNet clustering algorithm is further exemplified by the network lifetime graph. The network lifetime is defined as the time the first node in the network has a depleted battery. For this experiment, the memory component in the clustering pheromone formula (parameter a in the Equation (3.6)) was set to 0 (zero) and the energy component (parameter b in the Equation (3.6)) was set to 1. This way, energy rich sensors have greater probabilities of becoming a CH. Moreover, a Constant

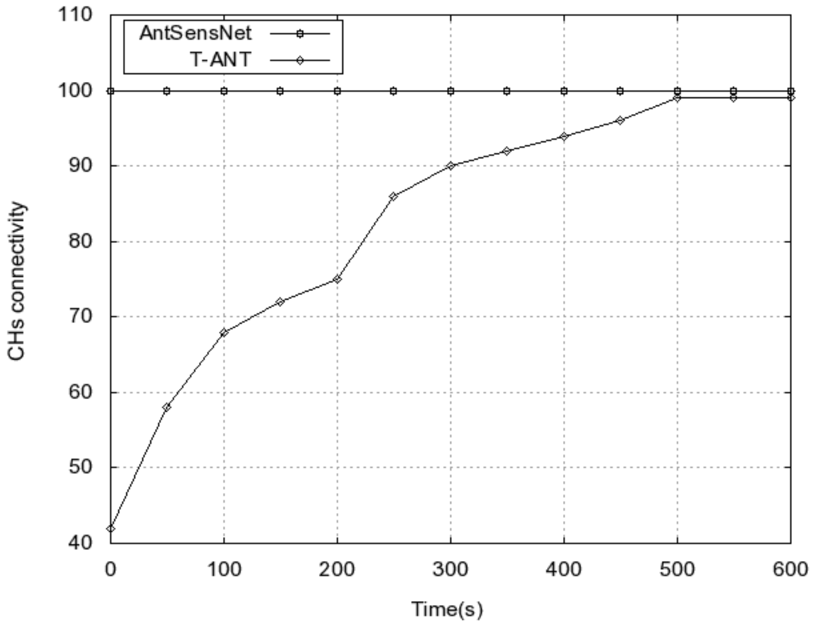

Figure 3.4 The CH connectivity at various simulation time for AntSensNet and T-ANT.

Bit Rate CBR traffic source was used to generate data traffic of 32-byte packets. All regular nodes sent the sink a packet/second on average. Non sending nodes fall into a sleep mode. Five simulations were carried out, where the value of the energy component varied. The initial energy of the scalar nodes was 0.1J and for the multimedia nodes, this initial energy was 0.5J in order to let the nodes disappear sooner. However, this does not change the behavior pattern of these protocols. It is clear that AntSensNet exhibits the longest lifetime with all nodes remaining fully functional. Test results show that AntSensNet achieves more than twice the cluster head lifetime of T-ANT. That can be explained by the fact that T-ANT selects any node as a cluster head. That node can be a normal node or a resource-rich node. If a normal node is selected as CH, it must carry out some important tasks in the routing process and that implies a bigger consummation of energy. A normal node acting as CH will deplete its battery first than a resource-rich node. AntSensNet, on the contrary, generally selects resource-rich nodes as CH. In that way the network lifetime (the time that the first node *dies*) is longer in AntSensNet than in T-ANT.

3.4.2 The Routing Process

This simulation was carried out after network clustering. The clustering parameters were $a = b = 0.5$, that is, in order to select a CH, the memory and energy components are equally important. The performance of this novel algorithm was compared with a well known

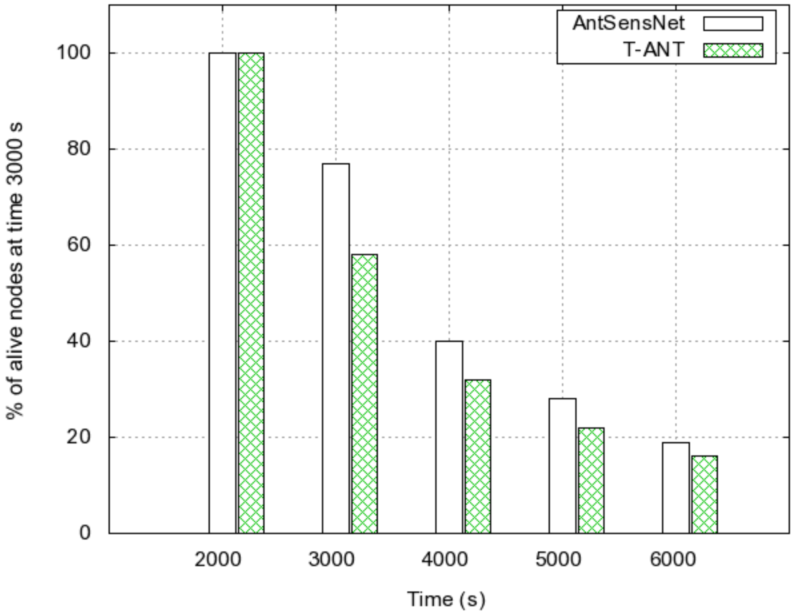

Figure 3.5 Network lifetime vs simulation time for T-ANT and AntSensNet.

protocol, AODV, supported in NS-2. AODV was modified in order to only consider the CHs at the moment they search for network routes. This way, a version of AODV can be compared with AntSensNet. In the base scenario, 400 nodes (200 scalars and 200 multimedia) are placed in a square area of 400 m × 400 m, and $R_{cluster} = 60m$. Simulations run for a total of 600 seconds every time.

Three performance metrics were taken into consideration : the *Packet Delivery Ratio (PDR)* involves the ratio of successfully delivered data packets to the total data packets sent from the source to their destination. *End-to-end delay* shows the amount of time needed to successfully deliver a packet from the source to the sink. *Routing overhead* indicates the ratio of routing packets transmitted to the total data packets delivered. Routing packets include control packets used for route discovery, route maintenance and pheromone updates.

To solely examine the effect of this novel routing algorithm, the network was moderately loaded. A Constant Bit Rate (CBR) traffic source model was used to generate data traffic between 32 and 1024-byte packets. Two traffic classes are produced by the nodes : multimedia traffic (with a size of 1024-byte packet) and scalar traffic (32-byte packet). Two nodes (one scalar and one multimedia) in the same cluster only send information to the sink. Obviously, multimedia traffic has higher priority than scalar traffic. Using the CBR model, the source nodes sent four data packets to the sink per second, on average.

Figure 3.6 shows the Packet Delivery Ratio (PDR) of AODV, AntSensNet Scalar traffic (ASNS) and AntSensNet Multimedia traffic (ASNM). In this case, the application defined the following QoS parameters for those traffic classes :

- For ASNS : in Equation (3.9), all the α values equal 0, except α_e (residual energy component), which is set to 1. The path's minimal residual energy must be superior to 0 (parameter $E_{\min}$ of the Equation (3.5)).
- For ASNM : in Equation (3.9), all the α values are 0, except α_ε (packet loss component), which is set to 1. That is, the packet loss in the discovered routes for this traffic class must be minimal.
- Both traffic classes have the ρ values (pheromone enforcement parameter) set to 0.7 for Equations (3.10) and (3.11).

We find that ASNS shows a comparable average PDR with AODV, while ASNM outperforms these two protocols after a few seconds. At the beginning, ASNM lacks sufficient information in order to find appropriate routes, but after a certain period of time, when the algorithm converges and the ants have gathered much node and route information, the quality of routes discovered for the ASNM is superior to those found by ASNS and AODV. Such results were expected, and this investigation confirms the authors' hypotheses.

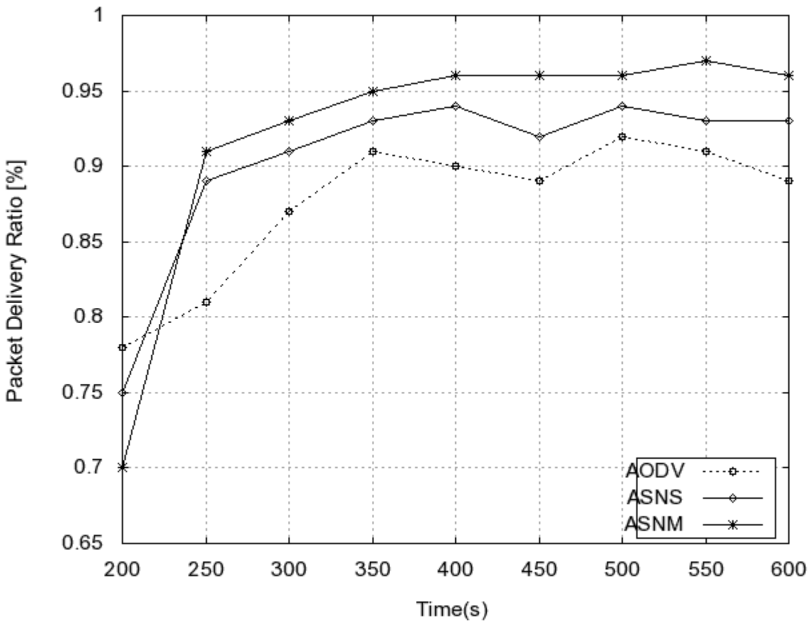

Figure 3.6 Packet Delivery Ratio.

In Figure 3.7, observe the mean end-to-end delay comparison between the protocols. For this experiment, the parameters for the ASNM traffic class were changed : all the α values are 0, except α_δ (cumulative queue delay parameter), which is set to 1. For this simulation, the maximal delay (parameter $D_{\max}$ in Equation (3.5)) is set at 8 msec. Notice that the end-to-end delays associated with the ASNM and ASNS packets are lower (and better) than those of AODV. Since multiple paths were discovered, when a path to the destination breaks, packets could immediately continue to be forwarded using another paths without a new route discovery process. Obviously, this reduced the end-to-end delay of the ASNM and ANSN packets. Since ASNS considers only energy as the main parameter for route discovery, not all packets were directed on the best path. Hence, ASNS generally requires more end-to-end delay than ASNM.

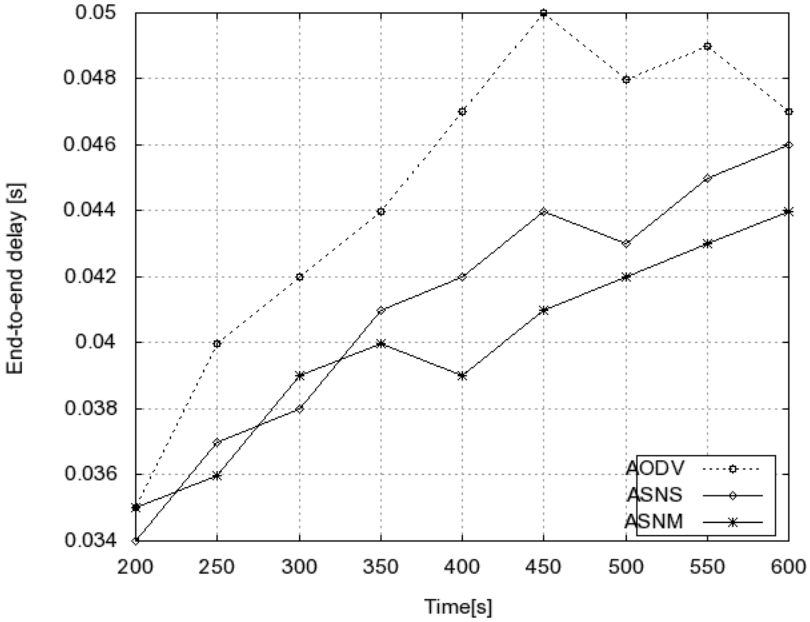

Figure 3.7 End-to-end delay.

Routing overhead is shown in Figure 3.8. Since extra FANT/BANT packets are required periodically to monitor and maintain path conditions, the routing overhead of AntSensNet is higher than AODV. This overhead can be reduced by embedding data into FANTs (a specimen of DANTs) and piggybacking the pheromone information on data packets if there is traffic between the sink and the CHs. Due to such periodic updates, AntSensNet constantly requires a certain amount of routing overhead.

3.4.3 Influence of Network Loading

Figure 3.9 depicts the effects of network loading on the performance metrics by increasing the number of data connections from 10 to 30. These results has been gotten from the average of ten simulations of 600 seconds each.

Figure 3.9a shows that the PDR for the protocols AODV and AntSensNet (ASN) has a declining trend when the number of data connection (512K CBR) is increased. The PDR of

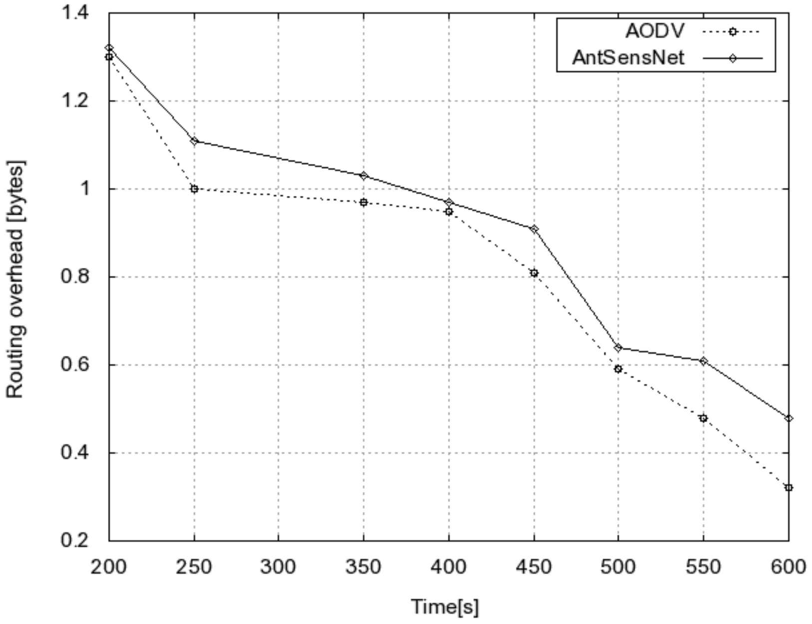

Figure 3.8 Routing overhead.

AODV dropped from 76% to 51% while that of ASN dropped from 92% to 58%. Both AODV and ASN are able to maintain >50% PDR in the latter case.

As Figure 3.9b shows, for a number of data connections of 10 nodes transmitting at the same time, the protocols have relatively small latency of <20ms. The latency increases gradually with the number of simultaneous data connections. It is worth to note that the difference in latency between the load at 30 data connections is about twice, i.e., from 75ms for ASN and 120ms for AODV, which is significant.

These results are explained by the AntSensNet's capability to find adapt to the network conditions, to find better routes and to use multiples routes.

3.4.4 Video Transmission

In this section we compare the capacity of protocols ASAR (Sun *et al.*, 2008) and TPGF (Shu *et al.*, 2010) versus our protocol AntSensNet to transmit video packets.

The network topology used is the same used in the previous simulations. Only a video sensor in all the network is capturing, encoding and sending a live video sequences to the sink. We use only two paths to send the packets (in TPGF and AntSensNet, for ASAR we use only a path). The video sequence is encoded according to H.264/AVC standard with a reference frame list of size five frames for compensated prediction. The video testing sequence *Foreman* (ASU, 2010) is used at QCIF resolution with 300 video frames at a frame rate of 30 fps with a

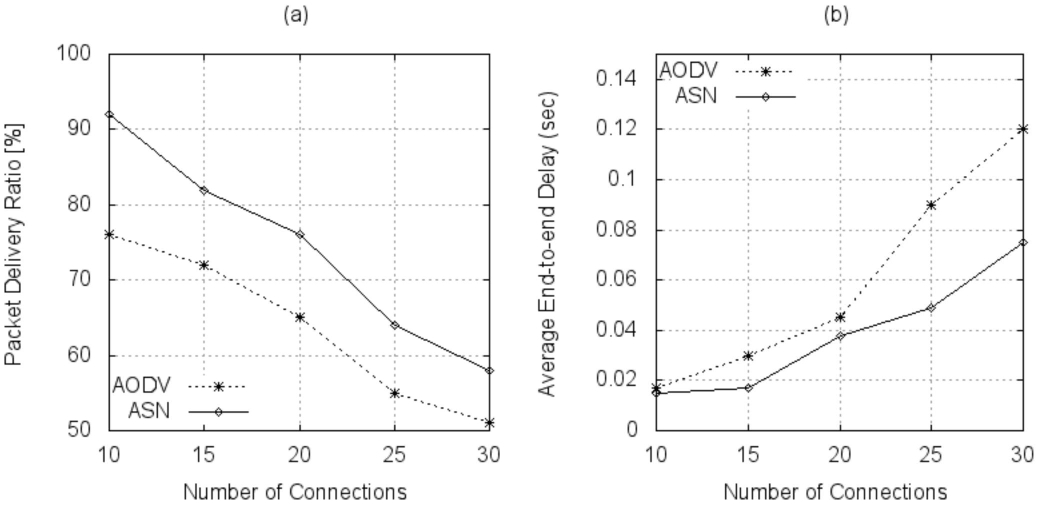

Figure 3.9 Results of varying number of data connections on (a) PDR and (b) average end-to-end delay

constant quantization step. In addition, the value of the parameter M_{REF} was set to 5 frames. The inter-frame period is 36 frames and is set to be equal with the transmission window. The video frames are encapsulated into packets of size 1,024 bytes. A text trace of the video file was created including the size of each frame and the time from the start of the video that the frame occurred. This text information was included within the data field of the packets in the simulation. As each packet was sent and received, a trace file was generated indicating the time segment number of the video being sent. After the simulation, the video file was reconstructed using the Evalvid software(Klaue *et al.*, 2003), expanded into uncompressed video using ffmpeg (Ke *et al.*, 2008), and compared to the original uncompressed source file again using the Evalvid software.

Figure 3.10 shows the average PSNR of the *Foreman* video. We can see that the video quality was higher for the simulations using AntSensNet when compared to the other protocols. This is because the protocols TPGF and ASAR are not able to handle correctly video content. They do not implement any distortion minimization rate control and they are only specialized in scalar data transmission. Conversely, AntSensNet is content-aware and and is able to take actions in order to minimize the video distortion.

3.5 Conclusion

The promising pace of technological growth has led to the design of sensors capable of sensing and producing multimedia data. However, as multimedia data contain images, video,

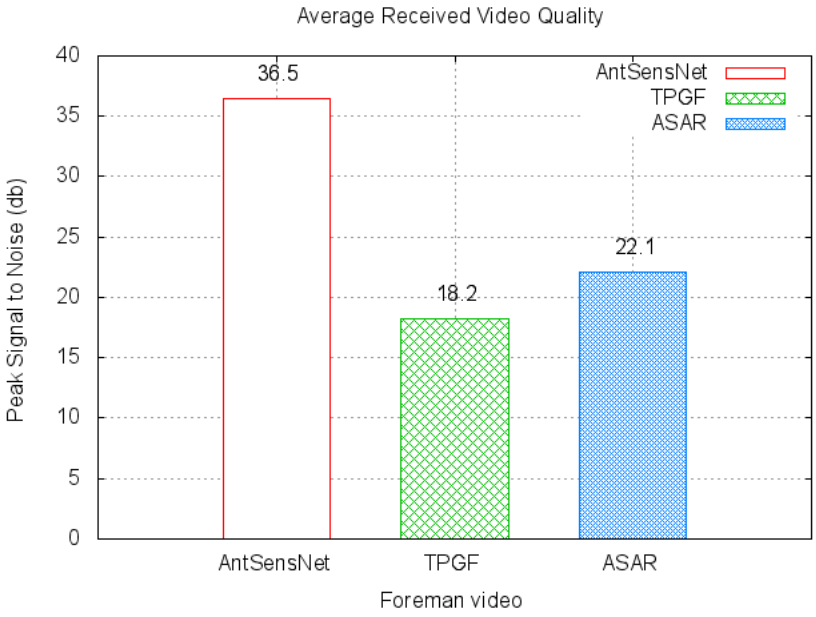

Figure 3.10 Received Video Quality of *Foreman* video

audio and scalar data, each deserves its own metrics. These characteristics of multimedia sensor networks depend on efficient methods in order to satisfy QoS requirements. Given such motivation, this paper proposes a QoS routing algorithm such as AntSensNet for WMSNs based on an Ant Colony optimization framework and a biologically inspired clustering process. The routing algorithm also offers different classes of traffic, adapted to the needs of applications. The clustering element uses special agents (ants) to guide the selection of CHs in a totally distributed manner. In comparison with T-ANT, another ant-based clustering algorithm, this novel clustering process achieves a permanent CH connection with lower energy costs. Routing comprises both reactive and proactive components. In a reactive path setup aimed at the classes of traffic in the multimedia sensor networks, the algorithm can select paths to meet the application QoS requirements, thus improving network performance. Multimedia data are sent over the found paths. Over the course of the session, paths are continuously monitored and improved in a proactive way. Simulation results show that the performance of AntSensNet outperforms the standard AODV in terms of delivery ratio, end-to-end delay and routing overhead.

Simulation results support that the proposed distortion reduction mechanism used to transport video packets results in better quality video than using other protocols for multimedia transport (TPGF and ASAR).

In future work, we intend to study the initialization method to populate routing tables with initial pheromone levels. As shown in the literature (Ying *et al.*, 2004), such mechanisms can further increase network efficiency. Other approaches to be studied include the integration of multiple sink-nodes as well as node mobility. Another improvement we plan to investigate is to extend the proposed architecture to a t cross-layer architecture proposed in this work to include a better interaction with a transport entity and the MAC sublayer. Similarly, Instead of the 802.11 MAC layer, we will investigate the use of Sensor MAC (SMAC) which is a MAC protocol designed for wireless sensor networks. SMAC has the potential to make the cross-layer architecture more energy efficient.

CHAPITRE 4

A DISTRIBUTED CONNECTION ADMISSION CONTROL STRATEGY FOR WIRELESS MULTIMEDIA SENSOR NETWORKS

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Abstract

Wireless Multimedia Sensor Networks (WMSN) is an evolution of typical Wireless sensor networks, where in addition to scalar data, devices in the network are able to retrieve video and audio streams, still images, from the environment. Providing QoS guarantees for the multimedia traffic in WMSNs requires sophisticated traffic management and admission control procedures. In this paper, taking multiple parameters into account, we propose a novel connection admission control scheme for this multimedia traffic. The proposed scheme is able to determine if a new flow can be admitted in the network considering the current link states and the energy of the nodes. The decision about accepting is taken in a distributed way, without trusting in a central entity to take this decision. In addition, our scheme works like a plug-in, being easily adaptable to any routing and MAC protocols. Our simulation results show the effectiveness of our approach to satisfy QoS requirements of flows and achieve fair bandwidth utilization and low jitter.

Keywords : quality of service, admission control, wireless multimedia sensor networks.

4.1 Introduction

Wireless Sensor Networks (WSN) have attracted attention from academia and industry in recent years, mainly due to the various applications that can be built on them. A WSN consists of spatially distributed sensor nodes. In a WSN, each sensor node is capable to independently perform some processing tasks and harvest information from the environment. Most of this sensed information is scalar (like pressure, temperature, light or location of objects). Furthermore, sensor nodes communicate with each other via radio in order to forward their sensed information to a central base station or perform some collaborative tasks such as data fusion with others nodes in the network. In general, most of the applications currently deployed on a WSN have low bandwidth demands in order to transmit their scalar data, and are usually delay and packet-lost tolerant (Akyildiz *et al.*, 2002).

More recently, the accelerated advance that has been experimented in the sensor hardware field, MEMS and embedded computing, coupled with the availability of new and inexpensive CMOS cameras and microphones that are capable to collect multimedia based data (image, video or sound) from the environment, allowed the emergence of so called WMSN. A WMSN is a network of wirelessly interconnected sensor nodes equipped with multimedia devices, such as cameras and microphones, and these nodes are able to retrieve video and audio streams, still images, as well as scalar sensor data (Akyildiz *et al.*, 2007). By elapsing time, WMSNs will become more and more popular and consequently these networks will allow the rise of a wide range of applications in both civilian and military areas which require visual and audio information such as multimedia surveillance sensor networks, traffic avoidance, enforcement and control systems, advanced health care delivery, automated assistance to elderly and family monitors, environmental monitoring and industrial process control.

The aforementioned applications require WMSNs provide mechanisms for delivering multimedia content to a certain level of QoS. These requirements are a consequence of the nature of the real time multimedia data such as high bandwidth demand, real-time delivery, tolerable end-to-end delay, and proper jitter and frame loss rate. Moreover, there are many different resource constraints in WMSNs involving energy, bandwidth, data rate, memory, buffer size and processing capability because of the physically small size of the sensors and the nature of the multimedia application that is typically producing a huge amount of data (Almalkawi *et al.*, 2010). Therefore, to meet the QoS requirements and to use the network scarce resource in a fair and efficient manner is not an easy task. In addition, guaranteeing QoS in a WMSN is a distributed task in nature, because of the use of error-prone wireless channels to communicate and its dynamic and infrastructure-less topology, ever changing. As a result, it is very hard for a central entity to have an exact map of the network state and take decisions about routing, for instance.

Much effort has been spent in protocols that provide QoS in WSN (Bhuyan *et al.*, 2010), but most of them do not take into accout an important factor when providing QoS to applications flows in the network : the dynamic CAC. CAC is an essential mechanism to accept or reject a new flow based on determined constraints requested by the application and the available resources in the network. Without an adequate admission control mechanism, the network can admit traffic flows that will generate communication links saturates and overloaded and the already admitted flows will experience unbearable performance degradation. In this paper, we propose a framework an end-to-end connection admission control mechanism that considers multiple QoS requirements simultaneously. Our framework :

- takes into account important QoS parameters, required by most application executing on a WMSN. These parameters include bandwidth, packet-error rate, delay and jitter.
- is implemented as a separate scheme on top of routing protocols such as AODV. This independence of the underlying routing protocol will allow our CAC to work as a plug-in for any protocol that needs an admission control scheme. Nevertheless, In order to reduce the overhead and improve the response time, our framework will use information gathered by the routing and MAC protocols about link and node states.
- guarantees the global end-to-end QoS requirements by the joint local decisions of the participating nodes. This operation is based on the concept of *Hop-by-Hop QoS contracts* introduced by Melodia et Akyildiz (2010).
- additionally makes possible the reservation of the required resources by the new flow, so that when the routing protocol begins to transmit packets, the network conditions for the new flow are not different from those who our framework found.

The remainder of the paper is organized as follows. Section 4.2 addresses related work. Section 4.3 presents our scheme for end-to-end call admission control. Section 4.4 describes simulation and results. Finally, Section 4.5 draws the main conclusions.

4.2 Related Work

Solutions have been proposed in the literature providing QoS support in Wireless Ad-Hoc Networks or Wireless Sensor Networks. Lee *et al.* (2000) propose INSIGNIA, a CAC framework that is independent of the routing protocol and is implement on top of it. The framework is based on an in-band signaling and soft-state resource management approach that is well suited to supporting mobility and end-to-end quality of service in highly dynamic environments where the network topology, node connectivity, and end-to-end quality of service are time varying. However, this framework collects the bandwidth information by itself (without taking into account the underlying routing and MAC information), generating high overhead, slow response and inefficiency.

The Contention-aware Admission Control Protocol (CACP) presented by Yang et Kravets (2005) aims to determine whether the available resources in the system can meet the bandwidth requirements of a new flow, while bandwidth levels for existing flows are maintained. CACP is governed by three main characteristics : a) Prediction of available bandwidth ; b) Contacting relevant neighborhoods and c) Prediction of bandwidth consumption by the flow. However, CACP has significant overhead since packet transmission using high power affects the ongoing transmission significantly and that makes unlikely the application of this framework due the importance of the energy in this kind of networks. Perceptive Admission Control (PAC), proposed by Chakeres *et al.* (2007) is another CAC protocols that enables a high QoS by limiting the flows in the networks. PAC monitors the wireless channel and dynamically adapts admission control decisions (increasing or decreasing the carrier sensing range) to enable high network utilization while preventing congestion. That can be an acceptable action for a ad-hoc network, but in a WSN, the extension of the sensing range will decrease the spatial reuse, and it will lead to some incorrect flow rejection decisions.

Zhu et Chlamtac (2006) introduce another framework which is compatible with existing AODV routing protocol, and achieves bandwidth estimation, QoS routing and admission decision by a cross layer cooperation between a IEEE 802.11 MAC and AODV-QoS routing protocol. Unfortunately, that solution is closely tied to the MAC protocol, and that makes the solution hard to implement if one wants to use other link protocols. Besides, this framework does not consider important QoS measures as jitter or end-to-end delay when making the flow admission decision.

With respect to WSN or WMSN, we cannot find many solutions to this problem in the literature, but we can highlight the following two : Yin *et al.* (2010) model an admission control algorithm for real-time traffic in a WSN, taking both delay and reliability into account. Also, their algorithm also provides a fairness-aware rate control for non-real-time control traffic. The scheme works in a cross-layer way, using information provided by the MAC layer. Although the reliability and delay are important factors for the transmission of multimedia data, this protocol forgets other important elements such as jitter or bandwidth used. Besides, the flow admission decision is taken only with local information, and the neighbors are not queried about their capacity when the new flow were admitted. Finally, Melodia et Akyildiz (2010), presents an excellent mechanism for admission control in WMSN. Their algorithm is based on the concept of *Hop-by-Hop Qos contracts*, where end-to-end QoS requirements for a new flow, are guaranteed by establishing local contracts. Each single device that participates in the communication is responsible for locally trying to guarantee the new flow performance objectives. The global, end-to-end objective is thus achieved by the joint local decision of the participating devices. Nevertheless, the scheme is strongly tied to UWB (Ultra Wide Band) radio technology and geographic routing, and these technologies cannot be found in many kinds of devices deployed in WMSN today.

Unlike our work, none of the previously proposed solutions consider the problem of satisfying multiple QoS constraints at the moment to make an admission control of a new flow and, at the same time, create a CAC framework that can be plugged in to a routing protocol to help it in the task to admit flows and which is capable to interact in a cross-layer way with the MAC layer to get the necessary information to accomplish such task.

4.3 Our Proposed Algorithm

The aim of connection admission control (CAC) is to determine whether the available resources in the network can meet the requirements of a new flow.

4.3.1 Network Model

In this work, a multimedia sensor network is represented as a graph $G(V, E)$, where $V = \{v_1, v_2, \cdots, v_N\}$ is a finite set of nodes in a determined finite-dimension terrain, with $N = |V|$, the number of nodes in the network, and E is the set of links between nodes, in other words, $e_{ij} \in E$ if and only if nodes v_i and v_j are within each other's transmission range. Node v_N represents the sink of the network. Each link e_{ij} has a knowledge about its available bandwidth β_{ij} and the energy spent in the transmission of a bit, which are dependent on the distance d_{ij} between nodes v_i and v_j (also i and j in the following for simplicity).

4.3.2 Operation of our CAC approach

Our CAC mechanism works in the following way : given a requested new flow $\Phi(\delta, \beta, \chi, \rho)$, with maximum end-to-end delay δ, minimum guaranteed bandwidth β, maximum end-to-end packet error rate χ and maximum end-to-end jitter ρ, generated at a node i that requires a connection with the sink, our algorithm will return "ACCEPT", if exists at lest a multi-hop path from i to the sink that can provide and guarantee all the new flow requirements or "REJECT", otherwise.

4.3.3 Assumptions

Our CAC scheme will operate as a plug-in for the routing protocol of each network node. The admission control mechanism is placed between the routing module and MAC layer (see Figure 4.1), and operates in a cross-layer, obtaining information from both the MAC layer and routing protocol, and accepting or rejecting a new connection for a flow of data the application layer wants to establish with the sink. We suppose that both MAC and routing layers are able to provide the required information to the CAC module. This information includes :

- *MAC Layer :* link states and statistic data such as average sent packets, node's neighborhood, energy used to transmit a packet, packet error, etc.
- *Routing Layer :* paths to the sink from a determined node, packet error rate, queues delay, etc.

This first assumption actually implicitly implies that MAC and routing protocols used by our CAC mechanism are QoS-aware protocols. Typically, that kind of protocols maintains and deals with this information, such as described by Bhuyan *et al.* (2010). It can also deduced here is the routing protocol knows at least a route from node i to the sink before performing admission control. Knowing the paths between any flow source node and the sink is an important requirement for our CAC mechanism.

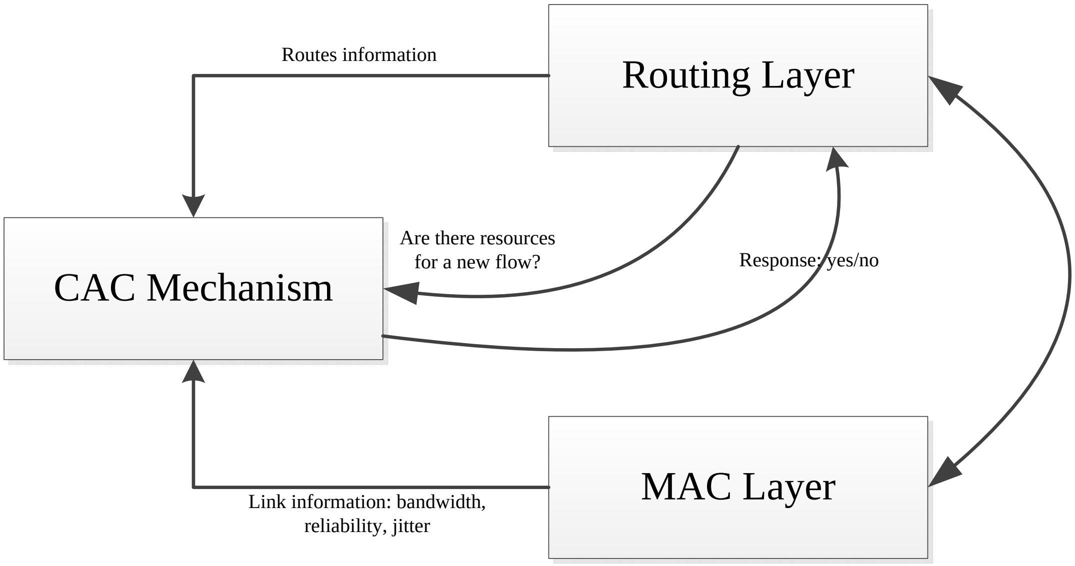

Figure 4.1 CAC Modelling

We also suppose that a node can estimate their available link bandwidth in any moment (for exemple, using the method presented by Alzate *et al.* (2008)) in a simple way. In the same way, an application can provide information of bandwidth required by each data flow.

CAC Mechanism Description

As discussed before, the goal of a CAC scheme is to provide decisions on a new flow admission with a certain QoS needs. If we are able to find a route providing the needed end-to-end QoS requirements for the new flow, then we can admit it in the network and the application can start transmit its packets.

Similarly to the solution presented by Melodia et Akyildiz (2010), we implement our CAC mechanism using the concept of *Hop-by-Hop QoS Contracts*. In our case, in order to determine if a route fulfills the end-to-end levels of quality of service required by a new data flow, each node that is part of the route is responsible for locally trying to guarantee given performance objectives, namely its contract. The global, end-to-end objective is thus achieved by the joint local decisions of the participating nodes. In other words, each node in the route has a QoS responsibility (a *contract*) derived from the end-to-end QoS requirements of the new flow. If each node in the route has enough resources to accomplish its local contract, the global needs of the new flow can be satisfied and as result of that, the new flow can be admitted.

Let us assume that a new flow $\Phi(\delta, \beta, \chi, \rho)$ is generated at node i and requires service. A multi-hop path from i to the sink needs to be established, with maximum end-to-end delay δ, minimum guaranteed bandwidth β, maximum end-to-end packet error rate χ, and maximum end-to-end jitter ρ. Now, by uniformly partitioning these end-to-end requirements at all hops, we can get the hop requirements. As was previously pointed out, if the hop requirement can achieved at each hop, the end-to-end QoS requirements can also be met. A node can satisfy the hop requirement by selecting next hop nodes based on link conditions. Clearly, the required bandwidth β needs to be provided at each hop. That is, for a given path p,

$$\beta \leq \beta_{ij} \tag{4.1}$$

where β_{ij} represents the available bandwidth of link (i, j) on path p. Since the additive nature of the delay, we can allow that the required end-to-end delay to be evenly divided at each hop. For example, if the first hop in a 10 hops route towards the sink, then one tenth of the total allowed end-to-end delay can be allowed to that hop. Then, the hop requirement for maximum delay (δ_{ij}) at each link (i, j) with route to the sink, can be expressed as :

$$\delta_{ij} = \frac{\delta}{\hat{N}_{ij}} \tag{4.2}$$

where $\hat{N}_{ij}$ denotes the maximum number of hops for all the routes from i to the sink when j is next hop. This information must be provided by the routing layer. A similar concept can be applied to the jitter ρ_{ij}, that is :

$$\rho_{ij} = \frac{\rho}{\hat{N}_{ij}}. \tag{4.3}$$

On the other hand, the packet error rate is multiplicative, and as result of that, the contract is a little different, but we hold the same concept of proportionality. That is,

$$1 - (1 - \chi_{ij})^{\hat{N}_{ij}} \leq \chi, \tag{4.4}$$

which leads to

$$\chi_{ij} \leq 1 - \sqrt[\hat{N}_{ij}]{(1 - \chi)}. \tag{4.5}$$

In that way, we have the four contracts each hop must achieve to get a new flow admitted. These values are computed by the source node i once, before the CAC operation begins, and they are used by each node in deciding the next hop in the route towards the sink. As can see, the contracts are based on information collected by the routing and MAC layer. Our CAC mechanism only use such information in the task of deciding if a new flow should be admitted or not.

Admission of new flows is regulated by an *connection admission control protocol*, which works as follows. When receiving a new flow connection request form its application layer, node i checks whether it has enough resource to accommodate this new flow while satisfy its QoS requirements. If so, it broadcasts an `CONTRACT_REQUEST` packet, with the required characteristics of the contract for the new flow being generated at i. If a node j, neighbor of i, has a route to the sink and is able to provide the requested service with the necessary QoS (that is, the node j has at least a link with another node in the route to the sink (different to i) that satisfies all the contracts aforementioned), it replies with an `CONTRACT_ ACCEPTED` control packet, which also includes the available level of batteries. Hence, node i receives an `CONTRACT_ ACCEPTED` packet from all neighbors able to satisfy the contract for the new flow. Among these, the best node j^* (this one with the highest battery level) is selected. The node source will then send `ADMISSION_ REQUEST` control packet to the selected node. This process is depicted in the pseudo code presented in the algorithms 4 and 5.

When a node has not enough resources to satisfy the required contract, i.e., β_{ij}, δ_{ij}, ρ_{ij}, χ_{ij} for the new flow, it sends immediately to the previous node a `CONTRACT_ REJECTED` packet. If no `CONTRACT_ ACCEPTED` packet is received, the CAC procedure is aborted for that node, and an `ADMISSION_ DENIED` packet is sent to the upstream node, which will put the downstream node in a blacklist in order to not contact it again, and the CAC procedure will continue with the next best node. If there is no more neighbor nodes to continue, the node will also send a `ADMISSION_ DENIED` control packet to the upstream node. When the flow originator node receives `ADMISSION_ DENIED` packets from all its neighbors, it will notify to the routing layer about the new flow cannot be admitted. The algorithms 6 and 7 present this process at any node in the network.

When a `ADMISSION_ REQUEST` packet arrives at the sink, the sink will issue the `CONNECTION_ ADMITTED` control packet to the corresponding source node, following the same route but in inverse sense. After receiving the `CONNECTION_ ADMITTED` packet, the source node will inform to the routing layer that the new flow has been admitted, that there is a route that satisfy new flow requirements and that it can send packets stores in its buffer for the flow to

ALGORITHM 4: Beginning of CAC at source node i

```
Input: A connection admission request for flow $\Phi(\delta, \beta, \chi, \rho)$
if not enough resources then
    Reject connection request for $\Phi$ ;
    return
end
Calculate Contract $\delta_{ij}, \beta_{ij}, \chi_{ij}, \rho_{ij}$ ;
Broadcast packet CONTRACT_REQ with Contract ;
while not TIMEOUT do
    Receive packet from a neighbor $h$;
    if received packet is CONTRACT_ACCEPT then
        Store $h$ info ;
    end
end
if a neighbor accepted Contract then
    // Best node = max energy
    $j^* \leftarrow$ Best neighbor among info received;
    // Initialize path to sink
    Path $\leftarrow [i]$ ;
    Send packet { ADMISSION_REQ, Contract, Path } to node $j^*$ ;
else
    Reject connection request
end
```

the sink. This process is shown by the algorithms 8 and 9.

4.4 Experimental Results

To assess the performance of our CAC mechanism, we conduct several simulations on the ns2 network simulator version 2.34 (ns, 2010). Various tests were carried out with diverse network topologies and conditions. For these experiences, we have modified AODV to use the route found by the CAC algorithm after the flow is admitted to transmit the packets. In addition, before the CAC started to work, we had found routes between each node and the sink, using the normal AODV mechanism for finding routes.

In our first experience, we show that our CAC scheme is able to get routes that satisfy the requirements of a new flow entering in the network. For this simulation, we considered a scenario consisting of a 1000 m x 1000 m terrain with 49 nodes deployed in a grid structure. The sink is located at the center of the terrain. Each node has a transmission range of 50 m. We use IEEE 802.11 as our MAC protocol and AODV as the routing protocol. We assume the channel capacity is 1 Mbps.

In this first scenario, we have three flows, each one generating traffic with bandwidth

ALGORITHM 5: Behavior of a intermediate node when it receives a CONTRACT_REQUEST

```
Input: A packet CONTRACT_REQ has arrived from node $i$
if Request has not been received before then
    if Contract can be satisfied and there is a route to sink then
        Reply with CONTRACT_ACCEPT battery_level to node $i$ ;
    else
        Reply with CONTRACT_REJECT to node $i$ ;
    end
end
```

ALGORITHM 6: An intermediate node receives an ADMISSION_REQ packet

```
Input: A packet { ADMISSION_REQ, Contract, Path } has arrived from node $i$
Broadcast packet CONTRACT_REQ with Contract ;
while not TIMEOUT do
    Receive packet from a neighbor $h$;
    if received packet is CONTRACT_ACCEPT then
        Store $h$ info ;
    end
end
if a neighbor accepted Contract then
    // Best node = max energy
    $j^* \leftarrow$ Best neighbor among info received;
    Add myself to Path ;
    Send packet { ADMISSION_REQ, Contract, Path } to node $j^*$;
else
    Send packet ADMISSION_DENIED to node $i$
end
```

requirement of 320 kbps, maximum end-to-end packet delivery delay of 20ms, packet error rate of 0% and maximum jitter of 10ms. Each flow generates a CBR traffic with a rate of 80 packets per second with a packet size of 512 bytes. The second flow is started 10 seconds after the first flow, and the third flow, 10 seconds after the second flow. Figure 4.2 shows the throughput of each of the three flows, and Figure 4.3 shows the average end-to-end packet delay for the three flows. The graphs confirms the advantages of our CAC scheme. For instance, a stable throughput for each flow is guaranteed once it is accepted and the requirements are obtained all the simulation time. Delays are also maintained all the duration of the transmission and with a low fluctuation (low jitter). The found routes are adequate for the flows and their requirements.

In a second scenario we compare flows with admission control versus flows without admission control in order to establish that the utilization of CAC is advantageous for the transmission of multimedia information and overpasses AODV data transmission when it

ALGORITHM 7: Behavior when an ADMISSION_DENIED packet arrives

Input: An {ADMISSION_DENIED, Path } packet has arrived from node j

```
// Add node $j$ to a blacklist
Blacklist $j$ ;
// Choose the next best node
if there is more neighbors then
    $j^* \leftarrow$ next best neighbor $\neq j$;
    Send packet { ADMISSION_REQ, Contract, Path } to node $j^*$;
else
    Remove myself from Path ;
    if I am the flow originator then
        Reject new flow ;
    else
        $i \leftarrow$ last node in Path ;
        Send { ADMISSION_DENIED, Path } packet to $i$ ;
    end
end
```

ALGORITHM 8: A sink received an ADMISSION_REQUEST packet

Input: An { ADMISSION_REQ, Contract, Path } packet has been received

```
$j \leftarrow$ Last node in Path ;
Send {CONNECTION_ADMITTED, Path } to node $j$;
```

does not use any admission control. In this scenario we also have a 1000 m x 1000 m terrain and 49 nodes deployed in a grid structure with the sink in the center of the terrain. There are 20 nodes in the network (chosen in a random way) transmitting CBR information to the sink. Ten of these data flow require 200 kbit/s bandwidth, 100 ms end-to-end delay and 0% packet error rate. The other ten flows need a bandwidth of 500 kbit/s, 100 ms end-to-end delay and until 10% for the packet error rate. Figure 4.4 and Figure 4.5 show the differences between flow data transmission with CAC and data transmission without CAC. Figure 4.4 show the average throughput of the two groups of flows where there is no QoS support in

ALGORITHM 9: An intermediate node received an ADMISSION_ REQUEST packet

Input: An { CONNECTION_ADMITTED, Path } packet has been received

```
if I am the originator of the new flow then
    Accept the new flow ;
else
    $j \leftarrow$ previous node of me in Path ;
    Send { CONNECTION_ADMITTED, Path } to node $j$ ;
end
```

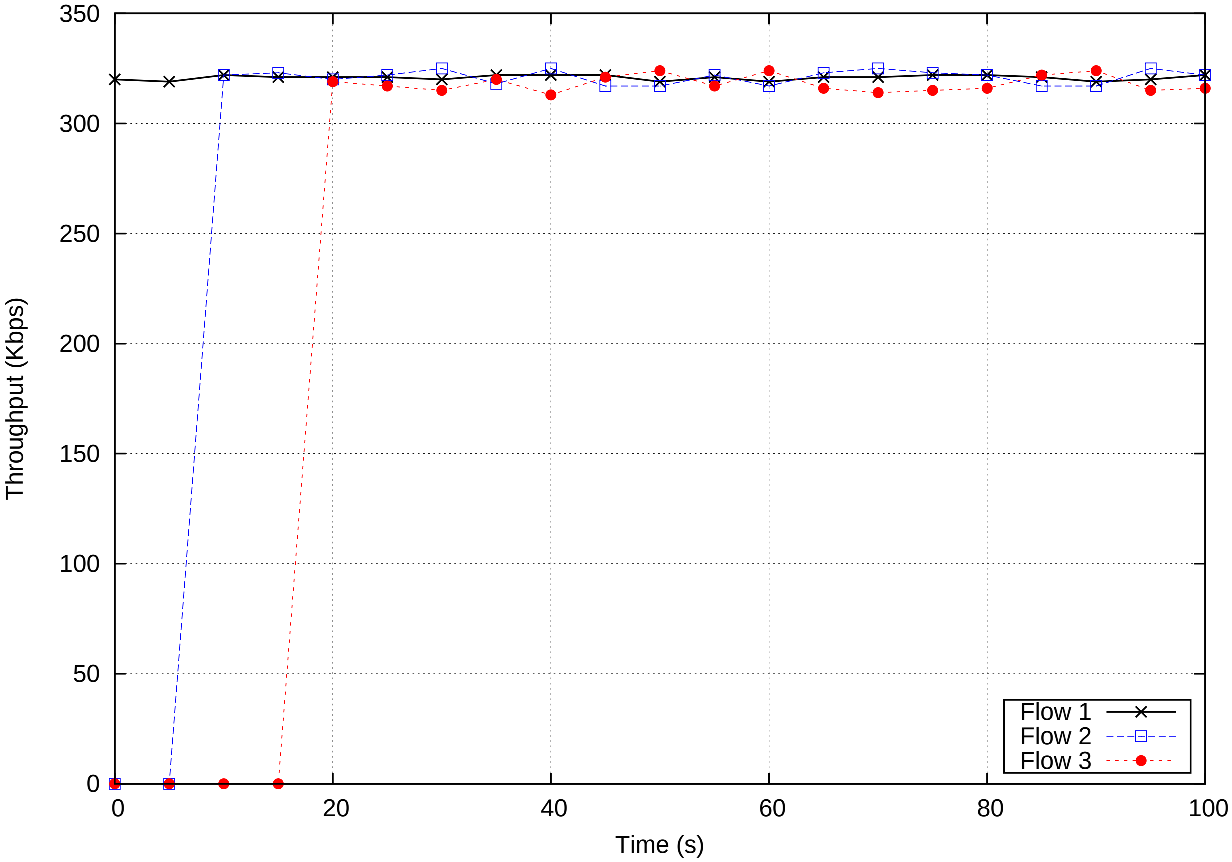

Figure 4.2 Throughput for flows with admission control

AODV. We can observe that in spite of all the flows were admitted, the throughput of each flow varies dramatically, the channel becomes congested and as result of that, there is a significant instability in the throughput of all flows. Figure 4.6 presents the average end-to-end delay for the two groups of flows when we do not use CAC. As expected, we find that with all flows transmitting data, there is a large delay for the packets, with a huge variation (big jitter). Such alterations do not satisfy flow demands and are not suitable for multimedia data transmission.

In contrast to the poor performance without QoS, the utilization of CAC achieve more stability for the admitted flows and as result of that, they can experience much better service. But, despite the fact only 8 flows are admitted (5 flows of the first group and and only 3 flows of the second group), these admitted flows can achieve their requirements the entire duration of the transmission. Compared to Figure 4.4, Figure 4.5 shows that the traffic throughput for each group of flows is nearly constant, flows in group 1 have a average throughput of about

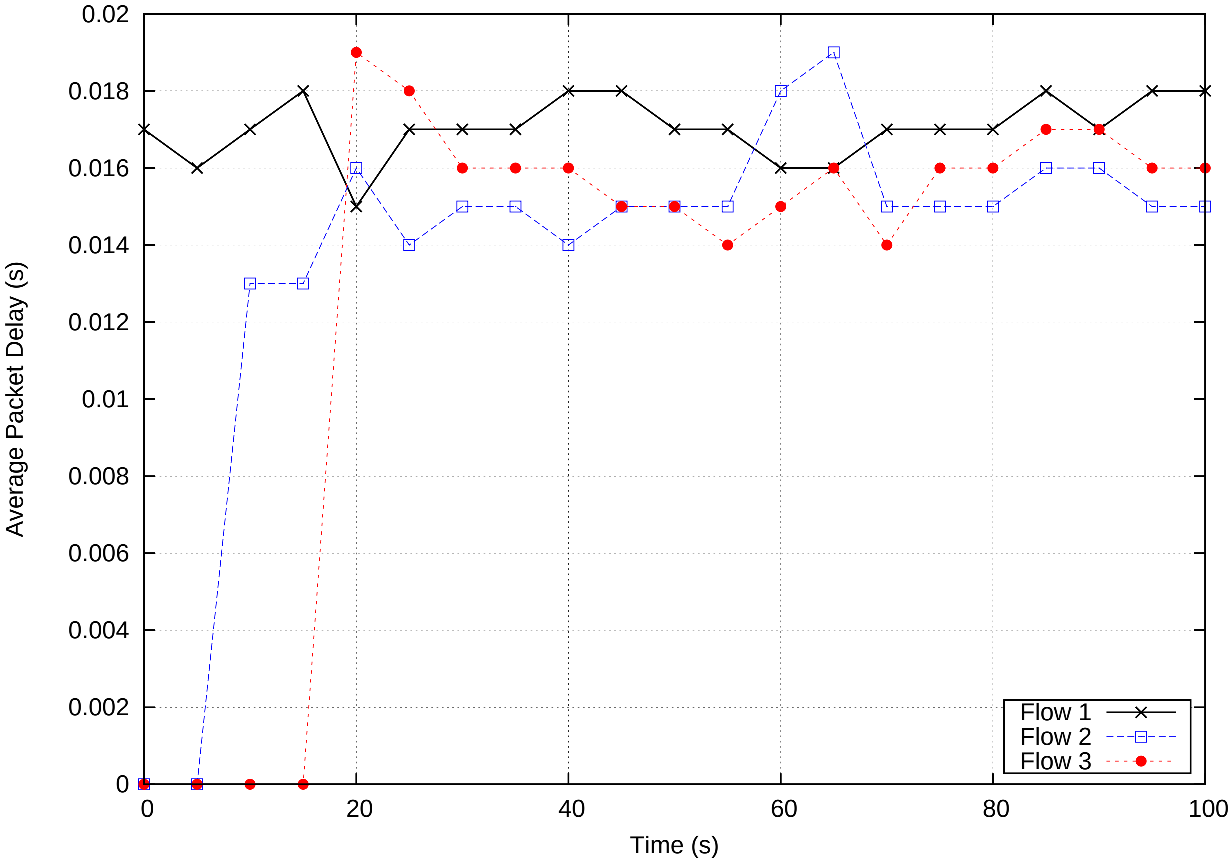

Figure 4.3 Packet delay for flows with admission control

200kbps, while flows in group 2 show a average throughput of about 490 kbps and match their requirements. The delay, shown in Figure 4.7, is very small compared with the delay obtained when we do not use CAC. The average end-to-end delays of the admitted flows of the two groups are below the required admission values. These short delays, along with a good obtained throughput demonstrate that our CAC mechanism can be used to sustain multimedia traffic, such as audio or video.

Next, we conduct a simulation using the same characteristics of the second scenario. In this case we will compare our CAC versus the admission control scheme implemented by AODV-QoS (Perkins et Belding-Royer, 2003) and AntSensNet (Cobo *et al.*, 2010) QoS protocols. AODV-Qos is a modification of the popular protocol AODV, but it supports getting routes considering bandwidth and time as QoS parameters. AntSensNet is based on ACO (Ant Colony Optimization) paradigm and is able to find routes taking into account the same parameters of our scheme (bandwidth, jitter, delay and packet lost), but also energy. In Table 4.1 we can observe the comparison among the three admission control schemes. There are 20

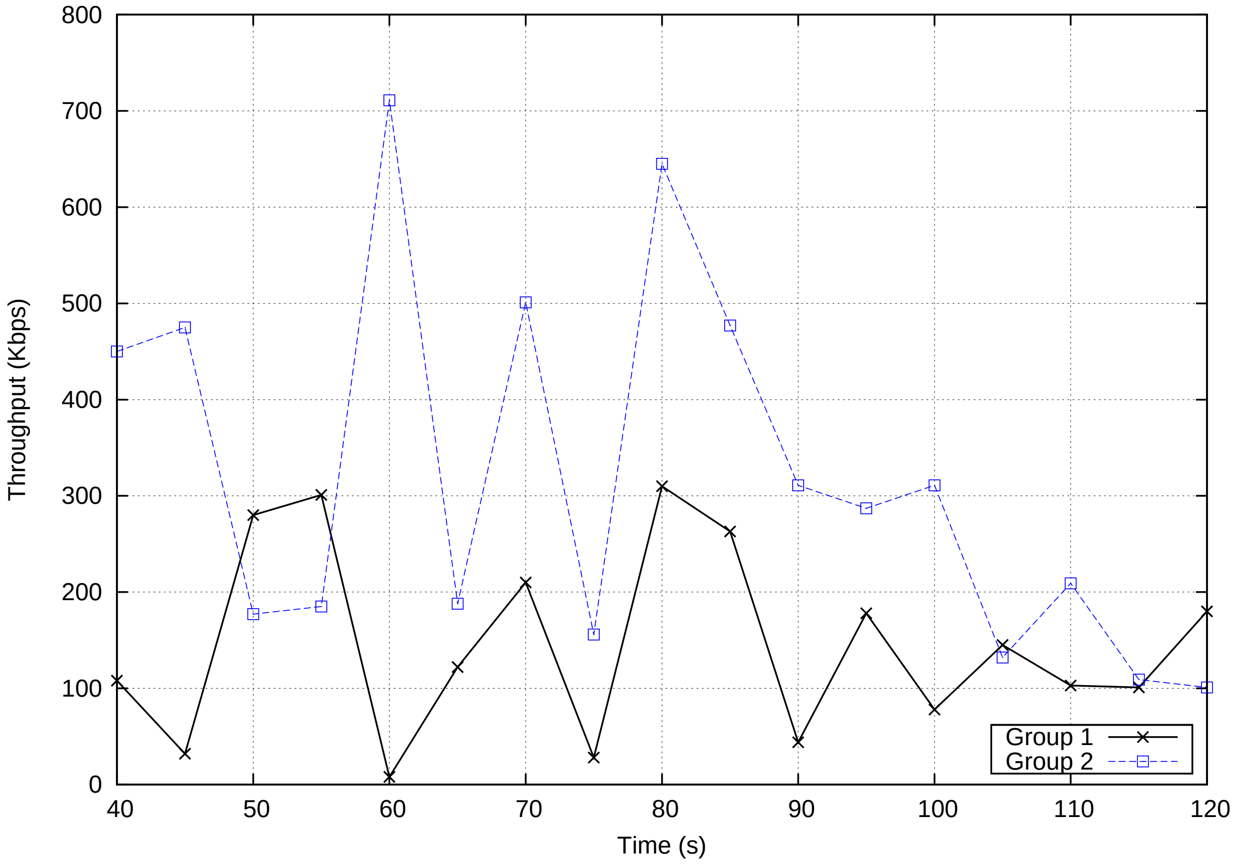

Figure 4.4 Throughput of flows without admission control

flows trying to get a connection to the sink. The number of admitted flows is similar in the three schemes. The reason because AODV-QoS admitted more flows is because it only uses bandwidth as a parameter of admission. AntSensNet generates more packets to admit flows because the decision to admit or not a flows is taken in a centralized way, i.e., the sink is the responsible to admit a flow or not. Both, AODV-QoS and our scheme, use a distributed way to admit flow, and the decision is taken by any node. The lifetime (time when the battery of a node is well drained) is better for AntSensNet because this protocol considers node energy at the moment to find routes. On the other hand, our scheme overpasses AODV-QoS in this respect. The energy is not important for this protocol, but when we choose a node to ask to admit a flow, that node is our "best node", it has more energy than the others.

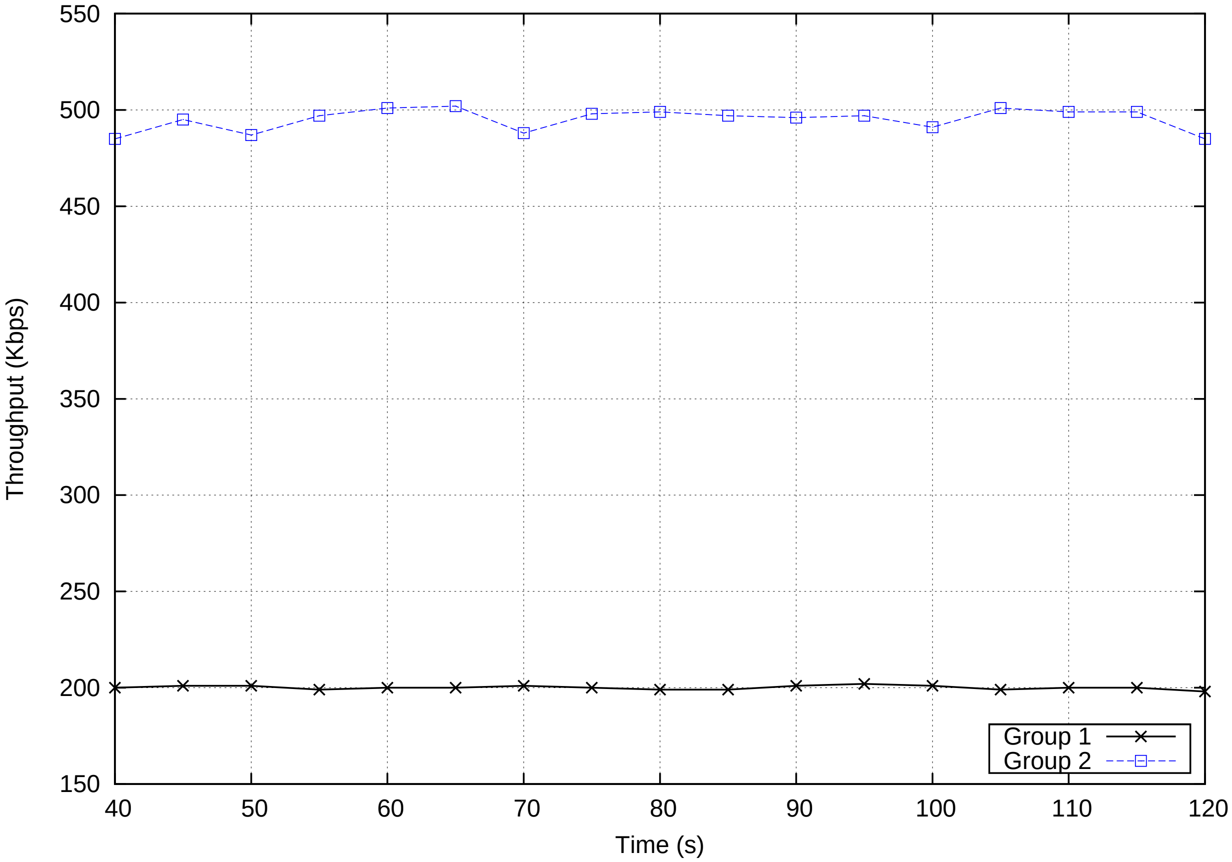

Figure 4.5 Throughput of flows with admission control

4.5 Conclusions

In this paper, we have presented a framework for connection admission control (CAC) to provide QoS in wireless multimedia sensor networks. Our CAC scheme is able to discover the route satisfying the multiple requirements (bandwidth, delay, packet error rate and jitter) and, on the basis of that, to determine whether a flow can be admitted. Our scheme is distributed (there is no a central entity what takes the admission decision) and adaptive to the link stated at the moment the new flow asks to be admitted. Performance evaluation shows that the proposed scheme is effective in supporting multimedia data transmission with QoS guarantees. In particular, delays are very low with low jitter, and throughput is maintained pretty constant in time.

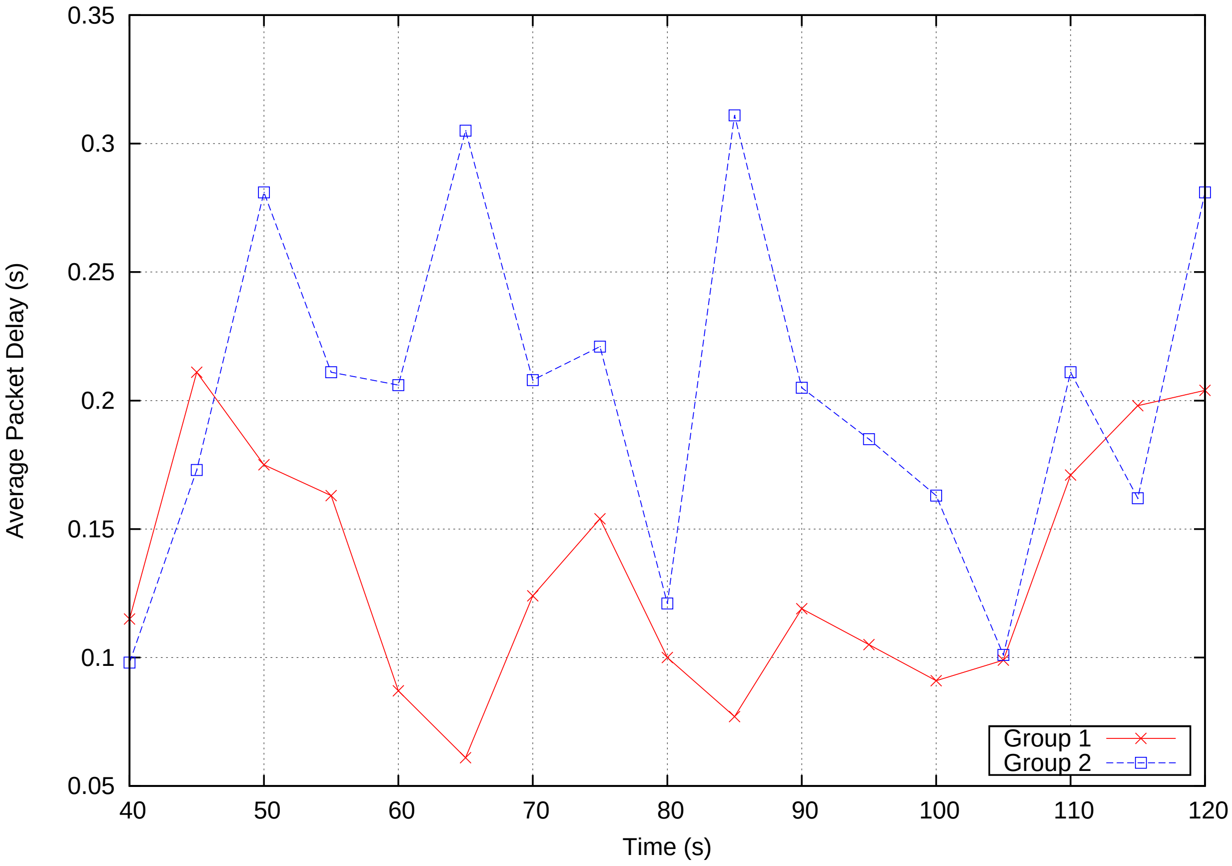

Figure 4.6 Packet delay of flows without admission control

Tableau 4.1 Comparison among admission control schemes

Protocol	**Admitted flows**	**Packets**	**Lifetime**
Our CAC	8	12	411 secs
AODV-QoS	11	10	304 secs
AntSensNet	8	24	612 secs

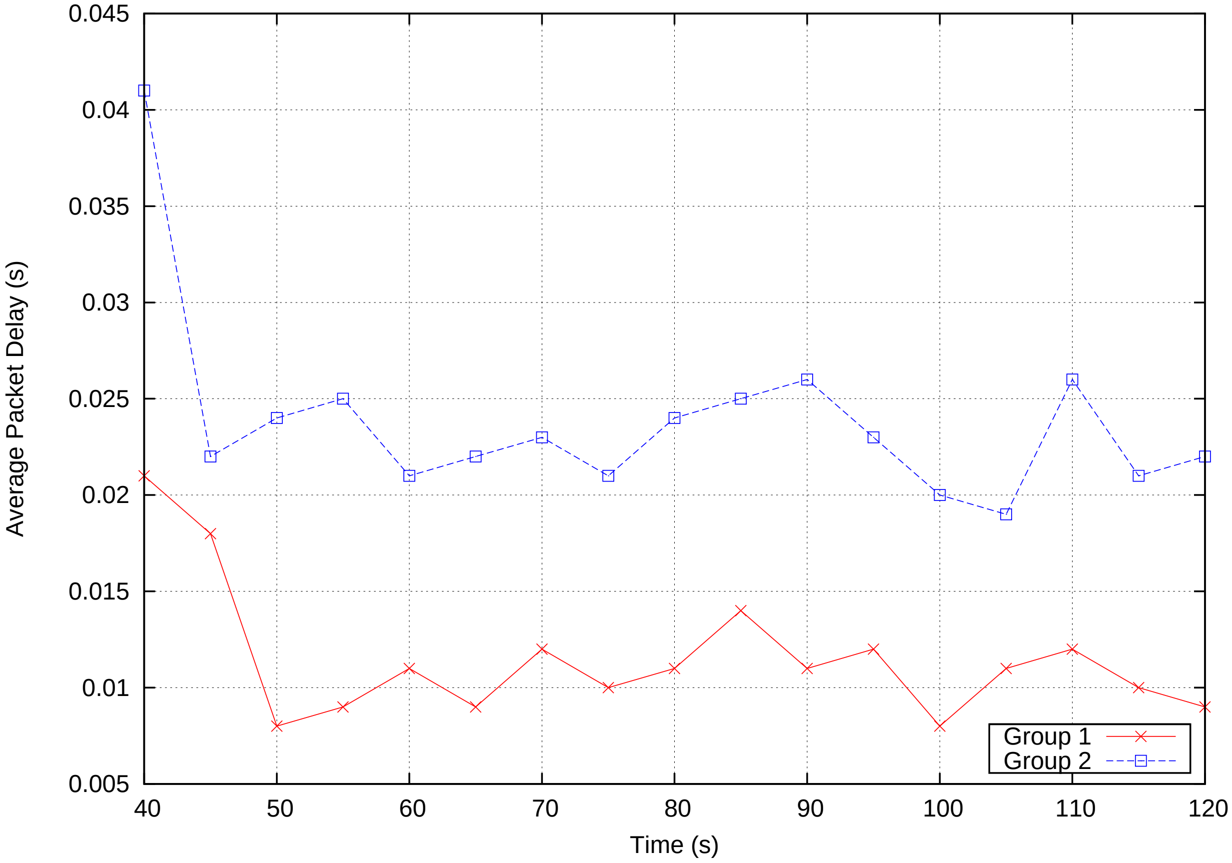

Figure 4.7 Packet delay of flows admission control

CHAPITRE 5

INTEGER PROGRAMMING FORMULATION AND GREEDY ALGORITHM FOR 3-D DIRECTIONAL SENSOR PLACEMENT IN WMSN

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Abstract

Conventional multimedia sensor deployment is generally based on a 2D directional sensing model. However, this model cannot accurately characterize the actual behavior of real multimedia (image/video) sensor networks. To remedy this deficiency, we propose a Minimum 3D Directional Sensor Placement (M3DSP) which aim at to determine the minimum number of connected directional multimedia sensor nodes and their configuration, needed to cover a set of control points in a given 3D space. The configuration of each deployed sensor is determined by three parameters which are sensing range, FoV and orientation. We present the exact ILP formulation for the problem and an approximate (but computationally efficient) greedy algorithm solution. We also evaluate different properties of the proposed solutions through extensive simulations.

Keywords : 3D, deployment, greedy algorithm, heuristics, linear programming, optimization, Wireless Multimedia Sensor Networks.

5.1 Introduction

The rapid development and progress of sensors, MEMS, embedded computing, in addition to the availability of inexpensive CMOS cameras and microphones coupled with the significant advances in distributed signal processing and multimedia source coding techniques, has allowed for the emergence of so called wireless multimedia sensor networks. As a result, WMSN (Akyildiz *et al.*, 2007) is a network of wirelessly interconnected smart nodes equipped with multimedia devices, such as cameras and microphones, and capable to retrieve video and audio streams, still images, as well as scalar sensor data. WMSNs promise a wide range of potential applications in both civilian and military areas which require visual and audio information such as video surveillance, traffic avoidance, law-enforcement reports, health care delivery, automated assistance to elderly telemedicine, industrial process control and environmental and structural monitoring. Besides, to successfully accomplish the assigned sensing tasks, the deployed sensors must both cover certain specific point-locations or the entire target sensing area, and form a connected network through multi-hop wireless communications. Therefore, an important issue in designing WMSNs is the appropriate placement of the sensor such that they can provide a *connected coverage* of a given area (Han *et al.*, 2008).

Sensors can be placed in an area of interest either deterministically or randomly. The choice of the deployment scheme depends highly on the type of sensors, application and the environment that the sensors will operate in. For some applications, random deployment of nodes is the only feasible option. This is particularly true for harsh environments such as a battle field or a disaster region. Depending on the node distribution and the level of redundancy, random node deployment can achieve the required performance goals. Alternatively, deterministic node deployment is viable and often necessary when sensors are expensive or when their operation is significantly affected by their position. Such scenarios include populating an area with highly precise seismic nodes, underwater WSN applications, and placing imaging and video sensors (Younis et Akkaya, 2008).

While conventional sensor networks often assume the *omni-directional sensing model* where each sensor can equally detect its environment in each direction, image/video sensors in a WMSN adopt the *directional sensing model.* In this model, the sensing region of each directional sensor is a sector of the sensing disk centered at the sensor with a sensing radius. In other words, directional sensors have the the notion of direction of measurement, i.e., they are capable of taking measurement only in a specific direction. When a sensor is facing to a direction and a target is in the sensing region of the sensor, we say that the direction of the sensor covers the target.

In general, these sensors are involved in three-dimensional (3D) application scenarios, which is much more difficult to analyze compared to two-dimensional deployment regions (Younis et Akkaya, 2008). That is the reason most existing works focus on the simplified 2D sensing model. However, according to Poduri *et al.* (2006) who have investigated the applicability of contemporary coverage analysis and placement strategies pursued for 2D spaces to 3D setups, many of the popular formulations, such as art-gallery and sphere-packing problems, which are optimally solvable in 2D, become NP-Hard in 3D. In addition to that, most placement approaches for directional multimedia sensors strives to enhance the quality of visual images and/or accuracy of the assessment of the detected objects. Other approaches focus on optimizing the sensor network after the sensors are randomly deployed in a sensor field. Therefore, there is a pressing need of efficient and effective 3D directional WMSN planning techniques.

In this paper, we study the problem of the connected coverage deployment in the context of directional multimedia sensor networks on a 3D sensing field. We provide an optimization framework that minimizes the number of sensors installed, while considering both 3D directional point covering and network connectivity constraints. We propose an Integer Linear Programming (ILP) formulation for the problem that allows to solve optimally in small size networks and to evaluate the impact of system parameters. We also propose an heuristic approach that allows to achieve good quality solution in short computing time, tackling also the optimization of larger network deployments.

The rest of the paper is organized as follows : Section 5.2 presents background and related work on this topic. Section 5.3 describes the 3D directional sensor network model and formally defines the problem. In Section 5.4, we present our resolution method based on a Greedy heuristic. In Section 5.5, we discuss our simulation results. Finally, Section 5.6 concludes the paper and points out some future directions.

5.2 Related Work

Extensive research on deterministic connected coverage deployment has been done for omni-directional sensor networks. Most work on this category of placement seeks to determine the "optimal" placement pattern, that is, to find the minimum number of nodes deployed.

Minimizing the number of sensor can take the form of an "art gallery" problem (O'Rourke, 1987), which aims to find the minimum set of locations for security guards inside a polygonal art gallery, such that the boundary of the entire gallery is visible by at least one of the security guards. González-Banos (2001) proposed a randomized algorithm to solve the art gallery problem in order to find locations for sensor nodes. However, in the art gallery problem, all security guards are assumed to have infinite vision if there is no obstacles. This assumption does not hold for directional WMSNs in which sensor nodes have limited sensing ranges. Besides, the problem does not require a connection between the guards, a very important exigence for the deployment of the nodes.

There is also some published works discussing the node deployment scheme through the maximization of coverage, using techniques as Virtual Force Algorithm (Wang *et al.*, 2007) or Tabu Search (Aitsaadi *et al.*, 2009). However, these works only considered the coverage constraint. They did not include the discussion about the connectivity, or they implicitly assumed that the sensor network formed by the obtained pattern was connected, regardless the transmission ranges of sensor nodes. Nevertheless, this assumption may not be true. To find the optimal node placement pattern subject to both coverage and connectivity constraints, Patel *et al.* (2005) have modeled the problem as an optimization problem that minimizes the number of required sensors nodes, under the constraints that a set of control points must be covered by at least a determined number of sensors and all the nodes are connected. However, the paper did not find a general solution. Instead, it discussed different options of regular sensor network deployment. These options include minimum cost placement or maximum lifetime placement.

Recently, a few research efforts have been devoted to directional sensor networks deployment. Ai et Abouzeid (2006) presented some algorithms for randomly deployed directional sensor networks to identify a minimal set of directions to cover the maximal number of point-locations. Cai *et al.* (2009), several scheduling algorithms were presented to divide a randomly deployed sensor network into subsets to alternatively cover a set of point-locations so as to prolong lifetime. Han *et al.* (2008) also presented several algorithms to deploy directional sensor networks. They were interested in the Connected Point-Coverage Deployment and the Connected Region-Coverage Deployment problems, and they solved both problems in a geometric way. They did not take into consideration important problems to any type of sensor networks as the connection to the sink or the energy intake in their algorithms. Besides, the authors only placement in a 2D space.

An interesting line of research is introduced by Osais *et al.* (2008, 2009, 2010), where the authors formulated an ILP (defined as Minimum Sensor Placement problem) about the placement of directional sensors, taking into account very important variables in this problem like the field of view for the sensors, their sensing range and the base station position. The model also considered point-coverage as well as connectivity among the deployed sensors. However, a 3D space was not considered in these models.

There exist only few references on 3D directional sensor network deployment in the literature. Ma *et al.* (2009) proposed a 3D directional sensor coverage-control model with tunable orientations. They used a virtual force analysis method to maximize the sensor area coverage after an initial random deployment. But in this method the number of sensors is not optimized and constraints like connectivity to the sink were not taken into account by the authors.

The 3D directional sensor placement problem is similar to the camera placement problem. Hörster et Lienhart (2006) developed a binary integer programming model to post-optimize the camera poses, after a random deployment, in order to increase coverage of the space observed. The exact model determines jointly for each camera the pan and tilt angle that maximizes the coverage of a 3D space. But this model is not directly applicable to a 3D directional sensor network, because it did not consider either the connectivity among sensors or between sensors and the sink.

Our work differs from prior work in a few aspects. First, the problem of covered-point connected deployment for 3D directional sensor networks is formulated, which can be solved exactly by the proposed ILP formulation in a small scale and approximately by the proposed Greedy algorithm in a large scale. Second, in such formulation we took into consideration very important elements in the WMSN design as the base station location. Finally, our proposed solution to deal with coverage by directional sensor with tunable orientation can treat the coverage by isotropic (omni-directional) sensors as a special case.

5.3 Problem Formulation

Controlled deployment is the ideal way pursued for the placement of multimedia sensor networks. These sensors need to be installed at precise places in a room and not randomly distributed on a outdoor field, mainly due in part to their cost and the importance to know their exact position for the applications. Therefore, our work offer to WMSN designers an efficient and effective model to help them make sure that their deterministically deployed network will perform as best as possible in a 3D sensor field.

5.3.1 Assumptions

The following assumptions are made about the model we are formulating :

- A directional multimedia sensor network consists of directional multimedia sensors and a base station, all of these are static.
- *Directional sensors* are responsible for sensing/monitoring environment as well as forwarding data they receive from other sensors towards the base station. These sensors have sectoral perception, that is, they capture information in a directional region, usually called Field of View (FoV).
- A *base station* is responsible for collecting all the data generated by sensor. The base station has sufficient hardware, sufficient software and constant power supply.
- The *control points* are locations in the sensor field which must be covered by a required number of sensors.
- The *feasible sites* are a set of points where it is possible to deploy the sensors in the sensor field.
- Either the control points or the feasible sites can regularly (i.e., a grid) or randomly be distributed.
- The predominant traffic in the network is the data traffic from sensors to the base station.

- We only consider convex 3D spaces without obstacles constricting the FoV of our multimedia sensors.
- As a result of that, the area covered by a sensor will be a circle with center in the sensor and radius equals to the sensing range of the sensor, and a control point will be covered by a sensor if the control point is within the coverage area of the sensor.

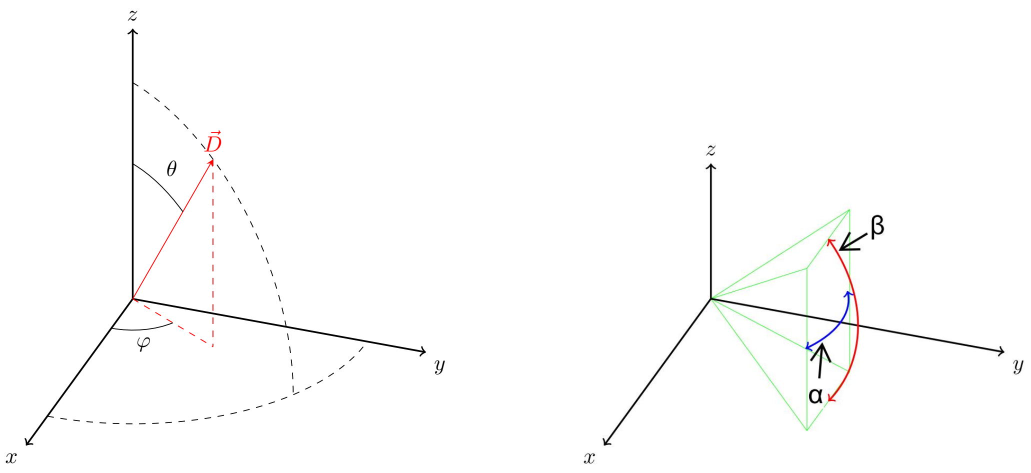
5.3.2 Sensing Model of 3D Directional Sensors

For simplicity, we also assume a *Boolean sensing model* (Hossain *et al.*, 2008). In this model, an event will be detected by a sensor if the occurrence of such event is within the sensing range of the sensor, otherwise not. Nevertheless, Different from the isotropic (omni-directional) 2D sensing model which is viewed as a whole circular area in a two-dimension plane, 3D sensing model focuses on two distinct features : 1) the sensor is located at a fixed 3D point, and its sensing direction is 3D rotatable around its location ; 2) the coverage area of a sensor is constrained by its FoV. Please note that, through the rest of the paper, unless otherwise mentioned, we use the terms *"sensors"* or *"nodes"* for simplicity to refer to wireless multimedia sensor including video and audio sensors having a directional view. Thus, we define a 3D directional sensing model as follows.

Our sensing model that defines the FoV of the sensors can be described by a pyramid. This pyramid can be completely characterized by the following parameters (please refer to Figure 5.1) :

1. $P = (x, y, z)$: the Cartesian coordinates which denote the location of the sensor in 3D space.
2. $\overrightarrow{D}$: the sensing direction (or orientation) of the directional sensor. This a vector that connect the apex of the pyramide (the point P) with the point located in the center of the base of the pyramid. Besides its length, this direction is defined by its *inclination* (θ) and its *azimuth* (φ). The inclination is the angle from the positive z-axis and the azimuth is the angle measured from the Cartesian plane xy.
3. α and β : the horizontal and vertical offset angles of the FoV around $\overrightarrow{D}$.
4. r_s : the sensing range of the directional sensor, beyond which a control point will not be covered. This value is the length of the vector $\overrightarrow{D}$.

In the ideal case, sensor' directions and offsets are continuous variables in the space. They could take any value from 0° to 360°. But, since our objective function, the (integer) number of cameras, is not continuous and differentiable, and in order to make our problem tractable, we approximate the continuous case by sampling poses, that is, we assume that directional sensors can only adopt a discrete set of values for these angles.



(a) Sensor direction (b) FoV amplitude

Figure 5.1 FoV parameters

5.3.3 Problem Statement

In this work, we aim at optimizing the overall network topology by properly selecting location and FoV of directional sensors in such a way that the total number of deployed sensors is minimized, under the constraints that each control point is covered by at least a given number of sensors and the resulting network is connected. We call this problem "Minimum 3D Directional Sensor Placement" or M3DSP. Unfortunately, M3DSP becomes the set covering problem in its simplest form , which is known to be NP-hard in the strong sense (Garey et Johnson, 1979). As a result, solving M3DSP becomes computationally prohibitive to obtain an exact optimal sensor placement solution for networks of realistic size. We therefore propose efficient and accurate approximation algorithms and heuristics.

5.3.4 Coverage by Directional Sensors

In the following, the term *space* denotes a convex physical three-dimensional room. We define that a control point in that space is *covered* by a sensor if that point is inside the sensor's FoV. To determine whether a control point c located at $C = (c_x, c_y, c_z)$ is covered by a sensor j with parameters $(P_j = (x_j, y_j, z_j), \overrightarrow{D_j}, \alpha_j, \beta_j, r_s)$, firstly we transform the control point's coordinate from world coordinate system to the field of view coordinate system. Figure 5.2 shows the process in 2D. To do this, we must follow the following two steps :

1. Translate the directional sensor's FoV to the origin of the coordinate system. The control point will be translated in the same way. As a consequence of that, the new translated coordinates for the control point, that we called C', can be gotten in the

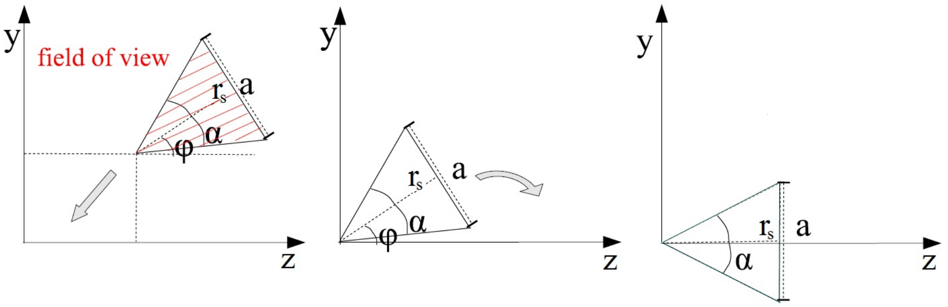


Figure 5.2 Process to know if a point is covered in 2D

following way :

$$C' = C - P_j = \begin{pmatrix} c_x \\ c_y \\ c_z \end{pmatrix} - \begin{pmatrix} x_j \\ y_j \\ z_j \end{pmatrix} = \begin{pmatrix} c_x - x_j \\ c_y - y_j \\ c_z - z_j \end{pmatrix} \tag{5.1}$$

2. Rotate the FoV and the translated control point around $z-$ and $x-$axis, by $\frac{\pi}{2} - \varphi$ and θ respectively, so that the sensing direction vector $\overrightarrow{D}$ becomes parallel to $z-$axis. In Equation (5.2), the variable C'' represents the new rotated-translated control point's coordinate :

$$C'' = \mathbf{R_x}(\theta) \cdot \mathbf{R_z}(\frac{\pi}{2} - \varphi) \cdot C' \tag{5.2}$$

where

$$\mathbf{R_z}(\gamma) = \begin{pmatrix} \cos\gamma & -\sin\gamma & 0 \\ \sin\gamma & \cos\gamma & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{5.3}$$

and

$$\mathbf{R_x}(\gamma) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\gamma & -\sin\gamma \\ 0 & \sin\gamma & \cos\gamma \end{pmatrix} \tag{5.4}$$

Concatenating the transformations gives the coordinates of a control point in the world coordinate system transformed to its coordinates in the directional sensor coordinate system :

$$C'' = \mathbf{R_x}(\theta) \cdot \mathbf{R_z}(\frac{\pi}{2} - \varphi) \cdot (C - P) \tag{5.5}$$

With $C'' = (c''_x, c''_y, c''_z)$ representing the control point coordinates in the FoV coordinate system, we are ready to do the covered point test (CPT). This test depends on the all FoV parameters and states that the control c is covered by a directional sensor j if all of the following conditions are true :

$$a) \quad c''_z \leq r_s \tag{5.6}$$

$$b) \quad -\tan\frac{\alpha}{2} \leq c''_y \leq \tan\frac{\alpha}{2} \tag{5.7}$$

$$c) \quad -\tan\frac{\beta}{2} \leq c''_x \leq \tan\frac{\beta}{2} \tag{5.8}$$

In other words, a 3D directional sensor at position $P_j = (x_j, y_j, z_j)$, orientation $\overrightarrow{D}$ (inclination $= \theta$, azimuth $= \varphi$), sensing range r_s and offset angles α and β covers a control point c located at $C = (c_x, c_y, c_z)$ if and only if 5.6–5.8 are satisfied.

5.3.5 Problem Modeling

In the following, we derive an ILP model to solve the M3DSP problem. We first define the following sets :

- Let $\mathcal{S} = \{1 \ldots N\}$ be the set feasible sites where the directional sensors can be installed. deploying sensors in the sensor field.
- Let $\Phi = \{1 \ldots M\}$ be the set of control points to monitor in the sensor field.
- Let Ψ be the set of all possible directions (or orientation) for a sensor.
- Let $\mathcal{A}$ be the set of all possible horizontal offset angles for a sensor. That is, the set of values that we can assign to the parameter α in the sensor's field of view.
- Let $\mathcal{B}$ be the set of all possible vertical offset angles for a sensor. That is, the set of values that the we can assign to the parameter β in the sensor's FoV.

Then, we define the following parameters

- Q, denote the minimum number of directional sensor that should cover every control point.
- r_s, the sensing range for all sensors.
- r_c, the communication range for all sensors.

We also define our constants :

- D, Adjacency matrix that summarizes connectivity between two sensors installed at two feasible sites. It is defined as

$$D_{ij} = \begin{cases} 1 & \text{if } dist(i,j) \leq r_c \text{ with } i \in \mathcal{S},\, j \in \mathcal{S},\, i \neq j, \\ 0 & \text{otherwise} \end{cases} \tag{5.9}$$

where $dist(\cdot)$ is the Euclidean distance between the position of the two involved devices

.

- B, Adjacency matrix that summarizes connectivity between a sensor installed at a feasible site and the WMSN base station. It is defined as

$$B_{ij} = \begin{cases} 1 & \text{if } dist_b(i) \leq r_c \text{ with } i \in \mathcal{S}, \\ 0 & \text{otherwise.} \end{cases} \tag{5.10}$$

  where $dist_b(\cdot)$ represents the Euclidean distance between a sensor and the base station.
- C, Adjacency matrix that summarizes the control point coverage by the directional sensors. This matrix is defined as

$$C_{ij}^{rab} = \begin{cases} 1, & \text{if a control point } m \in \Phi \text{ is within} \\ & \text{the coverage area of a sensor placed at location} \\ & i \in \mathcal{S} \text{ when its orientation is } r \in \Psi, \\ & \text{its horizontal offset angle is } a \in \mathcal{A} \\ & \text{and its vertical offset angle is } b \in \mathcal{B}, \\ 0, & \text{otherwise.} \end{cases} \tag{5.11}$$

- U_{ij}, Capacity of the wireless link between sensors $(i, j), i, j \in \mathcal{S}, i \neq j$.
- U_i^b, Capacity of the wireless link between sensor $i \in \mathcal{S}$ and the network base station.
- U_{max}, Maximum amount of data a directional sensor can handle (transmit and/or receive) per unit time (called the *node capacity*).
- R_i, The rate at which the information is generated at a sensor located at $i \in \mathcal{S}$

Finally, we define the following decision variables :

- x_i^{rab}, a binary variable defined as

$$x_i^{rab} = \begin{cases} 1, & \text{if a sensor is placed at location } i \in \mathcal{S} \\ & \text{with a orientation } r \in \Psi, \text{ a horizontal offset angle } a \in \mathcal{A} \\ & \text{and a vertical offset angle } b \in \mathcal{B}, \\ 0, & \text{otherwise.} \end{cases} \tag{5.12}$$

- y_{ij}, a binary variable defined as

$$y_{ij} = \begin{cases} 1, & \text{if there are is a sensor installed at site } i \in \mathcal{S} \\ & \text{that communicates with a sensor installed at site } j \in \mathcal{S}, i \neq j, \\ 0, & \text{otherwise.} \end{cases} \tag{5.13}$$

- y_i^b, a binary variable defined as

$$y_i^b = \begin{cases} 1, & \text{if there are is a sensor installed at site } i \in \mathcal{S} \\ & \text{that communicates directly with the base station,} \\ 0, & \text{otherwise.} \end{cases} \tag{5.14}$$

- f_{ij}, The data flow rate from sensor node i to sensor node j with $i, j \in \mathcal{S}$ and $i \neq j$.
- f_i^b, The data flow rate from sensor node i to the network base station, with $i \in \mathcal{S}$.

Thus, we can model our problem by the following optimization system. The following objective function aims at minimize the number of directional sensors that will be installed over the network.

$$\min \sum_{i \in \mathcal{S}} \sum_{r \in \Psi} \sum_{a \in \mathcal{A}} \sum_{b \in \mathcal{B}} x_i^{rab} \tag{5.15}$$

The optimization is subject to the following constraints :

The first constraint ensure that exactly one direction-offsets combination is assigned to each sensor :

$$\sum_{r \in \Psi} \sum_{a \in \mathcal{A}} \sum_{b \in \mathcal{B}} x_i^{rab} \leq 1 \qquad \forall i \in \mathcal{S} \tag{5.16}$$

The coverage requirement is represented by the following constraint

$$\left(\sum_{i \in \mathcal{S}} \sum_{r \in \Psi} \sum_{a \in \mathcal{A}} \sum_{b \in \mathcal{B}} x_i^{rab} \cdot C_{ij}^{rab} \right) \geq Q \qquad \forall j \in \Phi \tag{5.17}$$

which guarantees a full coverage of the monitored are such that every control point is covered by at least Q sensors.

A wireless link is established between two placement sites if two sensors are installed at those sites and they can communicate with each other. This is represented by the following constraint

$$y_{ij} \leq \frac{D_{ij}}{2} \cdot \left(\sum_{r \in \Psi} \sum_{a \in \mathcal{A}} \sum_{b \in \mathcal{B}} x_i^{rab} + \sum_{r \in \Psi} \sum_{a \in \mathcal{A}} \sum_{b \in \mathcal{B}} x_j^{rab} \right) \qquad \forall i, j \in \mathcal{S}, i \neq j \tag{5.18}$$

Similarly, a wireless link can be established between the base station and a placement site only if there is a sensor installed at that site and it can communicate with the base station. This is ensured by the following constraint :

$$y_i^b \leq B_i^s \cdot \sum_{r \in \Psi} \sum_{a \in \mathcal{A}} \sum_{b \in \mathcal{B}} x_i^{rab} \qquad \forall i \in \mathcal{S} \tag{5.19}$$

The following constraint ensures that the resulting network is connected, that is, the base station receives all the data generated by the installed sensor nodes.

$$\left(R_i \cdot \sum_{r \in \Psi} \sum_{a \in \mathcal{A}} \sum_{b \in \mathcal{B}} x_i^{rab} \right) + \sum_{j \in \mathcal{S}, j \neq i} f_{ij} - \sum_{j \in \mathcal{S}, j \neq i} f_{ji} \leq f_i^b \qquad \forall i \in \mathcal{S} \tag{5.20}$$

The sum of incoming and outgoing flow through a sensor node should not exceed its capacity and this is ensured by the following constraint :

$$\sum_{j \in \mathcal{S}, j \neq i} f_{ij} + \sum_{j \in \mathcal{S}, j \neq i} f_{ji} + f_i^b \leq U_{max} \cdot \sum_{r \in \Psi} \sum_{a \in \mathcal{A}} \sum_{b \in \mathcal{B}} x_i^{rab} \qquad \forall i \in \mathcal{S} \tag{5.21}$$

The remaining sets of constraints (5.22) and (5.23) ensure that the flow on a wireless link does not exceed link's capacity.

$$f_{ij} \leq U_{ij} \cdot y_{ij} \qquad i, j \in \mathcal{S}, i \neq j \tag{5.22}$$

$$f_i^b \leq U_i^b \cdot y_i^b \qquad \forall i \in \mathcal{S} \tag{5.23}$$

Finally, constraints (5.24) and (5.25) define the domain of each variable

$$x_i^{rab}, y_{ij}, y_i^b \in \{0, 1\} \qquad \forall i, j \in \mathcal{S}, i \neq j; r \in \Psi; a \in \mathcal{A}, b \in B \tag{5.24}$$

$$f_{ij}, f_i^b \in \mathbb{R}^+ \qquad \forall i \in \mathcal{S}, i \neq j \tag{5.25}$$

5.4 Proposed Heuristic

Though the solution of the ILP formulation provides the optimal solution for the M3DSP problem, it is not scalable for large problems instances. That is the reason we present here a greedy heuristic based polynomial-time algorithm for solving the problem in a approximate way.

To find a good solution, our algorithm follows two steps. The first step is the selection of a sensor set $\Gamma \subseteq \mathcal{S}$ with its respective FoV. We called this first step “The covering set finder”.

The sensors in this set cover all control points in the field (the set we previously defined as Φ). The second step creates a connected network from Γ, adding nodes from $\mathcal{S}$ to achieve this objective.

The pseudo-code for the first step is shown in Algorithm 10. The basic idea in this step can be described as follow : starting with an empty set Γ, we add sensors one by one until all control points are covered with Q sensors. Sensors that are not in Γ and cover at least one control point in the field with any combination of directions (set Ψ) and offsets (sets $\mathcal{A}$ and $\mathcal{B}$) are eligible to be added to Γ. Among the eligible sensors, the one covering the biggest number of control points will be selected.

A connected sensor network is the one in which all sensors can transmit the data they collect to the sink either directly or through neighboring sensors. But the fact of covering all control points does not assure a connected sensor network. Consequently, in the second step of our algorithm we try to make sure that sensor set Γ is connected. This is achieved by a procedure we called *connected set finder* which works on the set Γ^* consisting of the disconnected sensors in Γ which had been returned by the first step. This second step adds sensors to Γ one by one until all disconnected sensors can transmit their data to the sink through the newly added sensors. We also use the sensor set Π, which contains the sensors not selected in the first step. Obviously, a sensor eligible for being added to Γ must be chosen from Π. Among all eligible sensor, the one with the largest number of sensors in Γ^* becoming connected after adding it will be selected. The pseudo-code for the second step is shown in Algorithm 11.

At the end of the second step, the set Γ does not only cover all control point of the sensor field with the required quality, but also forms a connected network. We had deliberately forgotten the capacity constraints in order to obtain a simpler solution to this problem.

5.5 Computational Results

In this section, we present the results to evaluate the performance of the ILP model and we will also assess the quality of our greedy algorithm with respect to the exact (optimal) solution obtained from the ILP formulation. To find the optimal solution, we implement our model using IBM ILOG OPL CPLEX V6.3 (CPLEX, 2010). CPLEX is a mathematical programming and optimization tool that solves linear problems with continuous, integer, or mixed variables, using the branch-and-bound method.

ALGORITHM 10: Covering set finder

```
Input: $\mathcal{S}$ = the set of all possible sensor placement sites, $C$ = the matrix of coverage, $\Phi$ = the set
        of control points to cover
Output: $\Gamma$ = a collection of pairs (sensor placement site, FoV), that indicates the deployed
         sensors and its assigned FoV, $\Pi$ = the set of sensor sites without sensor deployed on it
$\Gamma \leftarrow \varnothing$ ;
$\Pi \leftarrow \mathcal{S}$ ;
/* $q$ = a vector with the number of sensors covering each control point */
$q_j \leftarrow 0 \quad \forall j \in \Phi$;
while $q_j < Q$ for some $j \in \Phi$ do
    if there is a sensor site $s \in \Pi$ covering at least a control point then
        $(i, k) \leftarrow$ a pair (the sensor $s \in \Pi$, FoV of $s$) that covers the most control points in $\Phi$;
        $\Gamma \leftarrow \Gamma \cup \{(i, k)\}$;
        $q_j \leftarrow q_j + 1 \qquad \forall j$ such that $(i, k)$ covers control point $j$;
        $\Pi \leftarrow \Pi - \{i\}$;
    end
    else
        /* since none of the non chosen nodes can cover additional control points,
           finish algorithm */
        Stop;
    end
end
```

5.5.1 Comparative Evaluation : Greedy vs CPLEX

First, to evaluate the quality of our heuristic versus the exact solution, we considered the effect of the number of placement sites and compared the objective function provided by our greedy algorithm to the lower bound provided by CPLEX. The measure of the objective function represent the number and FoV of each installed sensor required to cover all the control points. The experiments are set up as follows. Locations of control points and placement sites are uniformly generated for a sensor field of $100m \times 100m \times 100m$. There are 50 control points that need to be covered and one base station station (located at the center of the field) where all the traffic must be sent. Each sensor has a transmission range of 30m. The node capacity of each sensor is 40 Kbps and the link capacity of each wireless link is 10 Kbps. The rate of data generation is 512 bps for each sensor. The sensing range is 20m and each control point must be covered by at least one sensor.

The set of possible values for the FoV components (offsets and directions) are as follows :

– Inclinations = azimuths= $\{-45°, 0°, 45°\}$.

– $\mathcal{A} = \mathcal{B} = \{45°, 90°, 135°\}$

Table 5.1 shows the results for this first experiment. The first column indicates the number of possible placement sites in the sensor field. The second column indicates the value of the

ALGORITHM 11: Connected set finder

```
Input: $\Gamma$ = a collection of pairs (sensor placement site, FoV), that indicates the deployed sensors
        and its assigned FoV, $\Pi$ = the set of sensor sites without sensor deployed on it
Output: $\Gamma$
$\Gamma^* \leftarrow \Gamma$;
forall the $(v, k) \in \Gamma$ do
    if there is a path between $v$ and the sink then remove the connected node $v$
        $\Gamma^* \leftarrow \Gamma^* - \{(v, k)\}$;
    end
end
while $\Gamma^* \neq \varnothing$ do
    if $\Pi \neq \varnothing$ then
        Determine sensor $i \in \Pi$ that connect the highest number of sensors in $\Gamma$;
        $\Gamma \leftarrow \Gamma \cup \{(i, \varnothing)\}$;
        /* i.e., $\varnothing$ = the FoV in this case is not important                    */
        $\Pi \leftarrow \Pi - \{i\}$;
        Update $\Gamma^*$ by removing sensors that become connected due to addition of $i$ to $\Gamma$;
    end
    else
        /* It's impossible get a connected set $\Gamma$                                    */
        Stop;
    end
end
```

objective function obtained by CPLEX and the third column is the time spent by CPLEX to find this solution. The fourth column presents the value of the solution found by our greedy algorithm and the fifth column is time took the algorithm to get this solution. For each problem size, ten instances of the problem were randomly generated and the average was calculated.

Tableau 5.1 Comparison between found solutions for CPLEX and Greedy algorithm

Placement Sites	CPLEX		Greedy	
	Solution	Time	Solution	Time
80	15	7.3609s	34	0.0883s
100	14	43.504s	30	0.127s
150	13	190.885s	26	0.2515s
200	12	448.735s	22	0.3453s
220	11	755.997s	20	0.5025s
240	11	627.190s	21	0.61693s

As can be observed in the Table 5.1, we can infer that our greedy algorithm provides good solutions, that can be used by another schemes (maybe a tabu search or a simulated

Tableau 5.2 CPLEX vs Greedy algorithm with large instances

Placement Sites	CPLEX		Greedy	
	Solution	Time	Solution	Time
500	21	11.721h	28	0.2002h
1000	18	23.118h	24	0.2834h
1500	23	32.417h	26	0.3141h
2000	–	–	22	0.3815h
2500	–	–	27	0.4144h

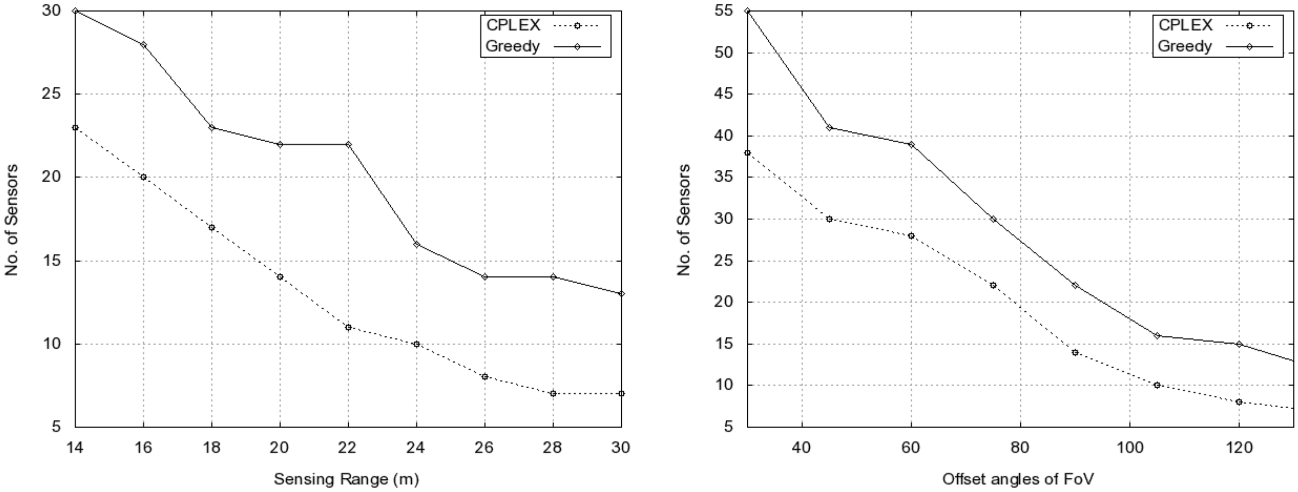
annealing algorithms) as a initial solution. With respect to the CPU times, it was predictable that an exact ILP resolution would not be suitable for large-sized networks and the excellent times obtained by the greedy algorithm demonstrate the this is a very efficient heuristic since the required computation time is less than a second for all instances.

The Table 5.2 shows how the behavior of Greedy algorithm with large instances of the problem. The time, in this case, is in hours. We can see the Greedy algorithm solution is close to the CPLEX solution, but the time to get this solution is very higher for CPLEX. Besides, when we work with a problem with a number of sites greater than to two thousand sites, CPLEX aborts with a “out-of-memory” message, and we cannot get a solution for such instances. Nevertheless, our Greedy algorithm has been able to get a good solution in a time inferior to one hour of execution.

As far as the reduction in the number of installed sensors is concerned, we can see that as the number of potential placement sites increases, the number of installed or deployed sensors decreases. Since more placement sites are available, better locations can be selected and one node can cover more control points, thus reducing the total number of installed sensors.

5.5.2 Impact of the Sensing Range

In practice, the value of the sensing range could vary depending on the physical properties of the sensors and on the type of signal they are sensing. We measured the impact of the sensing range in the found solution. To do that the number of placement sites was fixed to 200, the number of control points is 50 and the horizontal and vertical offsets of the possible FoV was fixed to 90° as well. The sensing range took the values between $14m$ and $30m$. Figure 5.3a shows that for both the exact solution and the greedy heuristic as the sensing range increase, less sensors are needed to cover the same number of control points. This behavior is as expected since a given sensor node can cover more control points, but there is always a 50% difference between the CPLEX result and the greedy algorithm result. The figure also demonstrated that for this problem size, the tendence in the found solutions are quite similar.



(a) Number of sensors required for different sensing ranges (b) Number of sensors required for different FoV

Figure 5.3 Performance Evaluation

5.5.3 Impact of the FoV

In practice, a directional sensor node must be able to adjust some parameters in order to get a better or accurate capture of the objects in its FoV. To evaluate the impact of the field of view on the solution found by CPLEX and by our greedy algorithm, we only considered the horizontal and vertical offsets of the sensor (the angles α and β) around the sensing direction (vector $\overrightarrow{D}$). We fixed the number of placement sites at 200 and the number of control points at 50. The sensing range is fixed at $20m$ and the communication radius is fixed at $30m$. We varied the angles α and β, but they are always equal, that is, the angles took always the same value. Figure 5.3b shows the variation of the number of installed sensor according to the selected FoV angles. Evidently, as the value of the angles decreases, more sensors are needed to cover the same set of control points. That is the expected result since with a smaller FoV, we covered less control points. We can also see that our greedy algorithm produce good results close to the results produced by CPLEX.

5.6 Conclusions

In this work we developed an ILP formulation for the determination of optimal 3D directional sensor placement. We also proposed a greedy heuristic to solve large instances of the model in a reasonable amount of CPU time. The main building block of this heuristic is to find connected sensor sets that cover the control points with the required quality. Simulations performed on a number of test instances indicate that the heuristic provides for acceptable results with respect to the exact solution of the derived ILP model, within low computation times. Despite its centralized aspect, our greedy algorithm exhibits low complexity and low computation times making its practical implementation adaptable for large-scale deployments.

As future research directions, we intend to develop a more sophisticated heuristic to improve the found solutions. For example, we can use the greedy algorithm as the initial solution for a tabu-search heuristic, because of good solution we found using that algorithm. Besides, we will also include the notion of energy consumption and network lifetime to our model, very important elements that all designers should take into account at the moment to plan a wireless sensor network. Finally, we intend to work on a distributed version of our approximative algorithms in order to obtain solutions in a shorter time.

CHAPITRE 6

DISCUSSION GÉNÉRALE

Dans ce chapitre, nous faisons une synthèse de nos travaux et contributions en regard de nos objectifs de recherche. Nous discutons également l'approche méthodologique employée et nous analysons les résultats obtenus.

6.1 Synthèse des travaux

La recherche menée dans cette thèse a donné lieu à trois articles de revues. Chacun de ces articles de revues traite d'un des points évoqués dans nos objectifs de recherche que nous allons récapitules dans les paragraphes ci-dessous. Un des articles de revues a déjà été publié tandis que les deux autres sont actuellement en cours d'évaluation.

Notre premier objectif de recherche porte sur l'analyse des mécanismes pour le support de la QdS dans les RCMSF et sur le déploiement de RCSF. Cet objectif a été réalisé grâce à une revue de littérature exhaustive sur ces domaines. De plus, nous avons souligné des faiblesses et des limitations des approches trouvées dans la littérature.

Partant de l'analyse, nos objectifs subséquents étaient de proposer un protocole qui supporte la QdS dans les RCMSF et d'en évaluer sa performance. Ces objectifs ont été réalisés au moyen d'un nouveau protocole que nous avons proposé et évalué. Ce protocole dénommé *AntSensNet*. Ce protocole est l'objet de l'article présenté dans le Chapitre 3. *AntSensNet* est spécifiquement conçu pour les RCMSF. Il est basé sur l'heuristique des colonies de fourmis et utilise un processus de création de grappes dans le réseau inspiré aussi par le comportement des fourmis. Le protocole peut trouver des chemins dans le réseau qui répondent aux exigences de qualité de service de l'application, et par conséquent améliore les performances du réseau. Les résultats des simulations montrent que la performance de notre protocole surpasse celle d'AODV en termes de délai de bout-en-bout, de taux de paquets perdus et de gigue. En outre, *AntSensNet* réalise un transport de paquets de vidéo avec une distorsion inférieure à celle des protocoles spécialisés comme TPGF ou ASAR.

Notre deuxième article présenté dans le Chapitre 4 nous permet de satisfaire l'objectif de la proposition d'un nouveau mécanisme de contrôle d'admission pour les RCMSF. Notre algorithme de contrôle d'admission applique une approche répartie pour répondre à la couche d'application si un nouveau flot doit être admis dans le réseau. La couche application spécifie les exigences du nouveau flot à partir de plusieurs métriques de QdS comme la gigue, la bande passante, le délai et le taux d'erreur. L'algorithme essaie de trouver une route qui satisfait les demandes du nouveau flot. Le flot n'est admis que si une route est trouvée. Notre algorithme diffère de la majorité des algorithmes proposés dans la littérature par son approche distribuée et le fait qu'il considère divers paramètres de QdS en même temps.

Les deux derniers objectifs sont satisfaits grâce au modèle mathématique et l'algorithme glouton présentés dans le troisième article (Chapitre 5). Dans cet article nous avons proposé un modèle mathématique pour minimiser le nombre de capteurs déployés dans une zone spécifique sous les contraintes de connectivité et de couverture. La solution du modèle nous fournit l'emplacement où installer chaque capteur ainsi que sa configuration. Nous avons aussi proposé un algorithme glouton qui nous permet de trouver de bonnes solutions pour des instances de grandes tailles, dans un temps raisonnable.

6.2 Méthodologie

Dans cette thèse, nous avons proposé de nouveaux algorithmes et des protocoles de communications, ainsi que des modèles mathématiques de programmation linaire. Pour les algorithmes et les protocoles, nous avons une validation par des simulations expérimentales. Deux outils ont été utilisés pour y arriver à savoir, le logiciel MATLAB (pour analyser les résultats) et le simulateur de réseaux NS-2.

Pour le problème de déploiement optimal, nous avons développé nos modèles de programmation à l'aide d'équations mathématiques. Par la suite, en utilisant l'outil ILOG CPLEX, nous avons obtenu des solutions optimales pour le modèle. Ces solutions nous procurent ainsi d'excellentes valeurs de référence.

Comme nous l'avons mentionné précédemment, puisque ces modèles sont très complexes à résoudre, nous avons également un algorithme glouton pour obtenir des solutions approximatives. Ce dernier a été implémenté à l'aide du langage de programmation Python.

Par ailleurs, pour générer nos résultats, nous avons suivi un mode opératoire formel et précis basé sur plusieurs batteries de tests qui ont permis de générer les valeurs moyennes ayant servi à la validation des résultats générés par nos heuristiques et algorithmes de simulation des protocoles.

6.3 Analyse des résultats

La validation numérique et par simulation de nos protocoles et algorithmes montrent qu'on obtient des résultats très satisfaisants.

Dans notre premier article, les résultats de la simulation en NS-2 ont montré que le protocole que nous avons proposée produit de meilleurs résultats en termes de durée de vie du réseau, de taux de perte de paquets et de surcharge du protocole que d'autres protocoles proposés dans la littérature scientifique récente.

Dans notre deuxième article, les résultats démontrent clairement et précisément que l'utilisation d'un mécanisme de contrôle d'admission est bénéfique pour le bon fonctionnement du réseau. On peut constater dans l'article la grande différence de performance d'un protocole quand il utilise le contrôle d'admission et quand il ne l'utilise pas.

Dans notre troisième article, les simulations démontrent que notre heuristique glouton génère de bons résultats, comparée à la solution optimale générée par CPLEX. Les temps pour trouver la solution sont aussi très bons avec des instances de grande taille.

CHAPITRE 7

CONCLUSION

Dans ce chapitre de conclusion, nous mettrons en évidence les différentes contributions de cette thèse. Par la suite, nous exposerons les limitations de nos travaux et, enfin, nous terminerons avec nos recommandations pour des recherches futures.

7.1 Sommaire des contributions de la thèse

Cette thèse a donné lieu à plusieurs contributions au niveau de la gestion de la QdS pour les RCMSF et la planification des réseaux de capteurs directionnels, qui étaient les éléments primordiaux de notre objectif principal. Voici un bref résumé des contributions qui nous ont permis d'atteindre notre objectif.

- Proposition d'un nouveau protocole pour la gestion de la QdS dans les RCMSF. Ce protocole, appelé *AntSensNet*, est basé sur l'heuristique de la colonie de fourmis. À partir des exigences demandées par la couche application, le protocole est capable de déterminer des routes qui satisfont de telles demandes. Le protocole est capable de transporter des données hétérogènes qui sont typiques dans les RCMSF. Ces données incluent l'information scalaire (température, pression, lumière, etc.) qui est produite par les capteurs normaux ainsi que l'information multimédia (vidéo, audio, images) qui est produite par les capteurs multimédia. De plus, le protocole est capable d'établir des priorités pour les paquets à partir du type d'information qui se trouve dans les paquets. Ce faisant, il est possible de transmettre en temps réel de la vidéo ou l'audio dans le réseau. Finalement, le protocole utilise un mécanisme de mise en grappe du réseau pour faire de manière plus efficace le transport de l'information et étendre la durée de vie du réseau.
- Proposition d'un nouvel algorithme de contrôle d'admission pour les RCMSF. Cet algorithme est capable de déterminer si le réseau a assez de ressourcés pour satisfaire les demandes d'un nouveau flot de données qui va être généré par un nœud du réseau. L'algorithme essaie de trouver une route dans le réseau avec les caractéristiques demandées d'une façon répartie et, à partir de l'état et l'information recueillie de chaque nœud, répondre positivement ou négativement à la requête d'admission du nouveau flot.
- Modélisation et résolution du problème de planification optimale du placement dans un espace 3D des capteurs directionnels dans un RCMSF, dans le but de minimiser le

nombre de capteurs déployés sous les contraintes de couverture et connectivité. CPLEX a été utilisé pour résoudre ce modèle de façon exacte. Ces solutions nous offrent une borne supérieure, en termes de nombre de capteurs déployés ainsi que leur configuration, pour les algorithmes qui essaient de trouver une solution non exacte au modèle. En outre, nous avons développé une heuristique gloutonne pour trouver une solution acceptable (par rapport à la solution exacte) aux instances de grandes tailles dans un temps raisonnable.

7.2 Limitations de la solution proposée

Malgré les contributions énoncées ci-dessus, notre travail présente certaines limitations dont nous pouvons citer :

- Une première limitation serait l'utilisation du protocole IEEE 802.11 comme le protocole de la couche MAC pour les simulations de notre protocole *AntSensNet*. Il y a des auteurs dans la littérature qui ne considèrent pas ce protocole comme adéquat ou réaliste pour les RCMSF. On peut voir aussi dans la littérature que les capteurs utilisent des protocoles de la couche MAC qui sont plus économiseurs d'énergie et, en conséquence, idéaux pour ce type de réseau.
- Une autre limitation concerne l'algorithme de contrôle d'admission et sa dépendance de l'information fournie par des entités externes comme les protocoles de la couche réseau et MAC. Cela implique l'obligation d'adapter l'algorithme à chaque protocole de réseau ou MAC qui l'utilisera. Par conséquent, l'implantation, l'installation et l'utilisation postérieure du mécanisme de contrôle d'admission deviennent une tâche exténuante.
- Une dernière limitation concerne la résolution exacte des modèles mathématiques présentés dans le Chapitre 5. Ces modèles sont très complexes à résoudre. De ce fait, seulement des problèmes de petite taille peuvent être résolus en un temps raisonnable. En plus, on n'a considéré que des capteurs directionnels avec le même rayon de détection pour simplifier le modèle, mais cela est aussi une limitation importante de notre travail de recherche.

7.3 Améliorations futures

Il reste beaucoup de choses à faire pour la gestion et le support de la QdS dans lesRCMSF. Nous présentons ci-après quelques pistes.

Une première piste de recherche serait d'améliorer la performance du protocole *AntSensNet* en trouvant des mécanismes qui permettront de remplir les tables de phénomènes des têtes de grappes avant de commencer les tâches de routage. Des articles recensés dans la littérature montrent que ce mécanisme aide à augmenter l'efficacité du réseau. On peut aussi faire de recherches sur la façon d'inclure des éléments intéressants au protocole comme la mobilité des nœuds ou l'intégration avec des réseaux à plusieurs SINKs.

En continuant avec notre protocole *AntSensNet*, une seconde piste de recherche serait d'améliorer le processus de mise en grappe utilisé par le protocole. Notre mécanisme crée des grappes autour des capteurs les plus puissants du réseau, mais au moment où ces capteurs têtes de grappe finissent de fonctionner, dû par exemple à un épuisement de leur batterie, les autres capteurs doivent se joindre aux grappes plus proches d'eux. Ce processus est simple et rapide, mais il introduit un problème de surcharge de trafic au niveau des grappes qui reçoivent les capteurs qui appartenaient aux grappes disparues. On pourrait rechercher des méthodes efficaces pour former de nouvelles grappes à la disparition d'une grappe donnée.

Une troisième piste consisterait à étendre notre modèle pour le placement de capteurs directionnels dans un espace 3D en prenant en compte de possibles obstacles qui pourraient se trouver sur le lieu de déploiement. Notre modèle actuel ne considère pas le cas où il y a des obstacles entre le capteur et le point d'intérêt qu'il doit couvrir. La modélisation du problème avec des obstacles dans un espace 3D n'est pas simple et on a besoin de beaucoup de recherche pour lui trouver une bonne solution. Finalement, une autre piste serait d'aborder la solution computationnelle du modèle en utilisant une heuristique différente de celle que nous avons utilisé. La solution avec un algorithme glouton produit de bons résultats dans un temps excellent, mais si on a besoin de solutions plus proches de la solution exacte pour des instances de grandes tailles, on pourrait développer une recherche Taboue et utiliser les résultats de l'algorithme glouton comme la solution initiale à partir de laquelle l'algorithme Tabou essaierait de découvrir de meilleures solutions.

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