Context Aware Clustering in VANETs: a Game Theoretic Perspective

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***Abstract*—This paper focuses on a particular application of coalitional game theory to Vehicular Ad Hoc Networks (VANET), involving only vehicular-to-vehicular communications. Moreover, networking is performed in an ad hoc basis to pursue full context awareness of vehicles. The proposed approach relies upon the setting up of cluster as soon as convoys temporarily arise in traffic dynamics. First, we define a utility function for each node under the hypothesis of being an ordinary node, cluster head or free node. We further prove that a selfish approach is suboptimal when compared to a game of coalition. Then, the communication between clusters (*inter clusters* communications) has been implicitly modelled according to this approach. Finally, from the simulation results, it is shown that a coalitional game outperforms a selfish approach for different nodes spatial deployment and mobility patterns.**

***Index Terms*—VANET; V2V Communications, Context Awareness, Dynamic Clustering, Game Theory.**

I. Introduction

Recent advance in wireless technologies has made vehicle-to-vehicle (V2V) communications affordable. Potential applications of the vehicular ad hoc networks (VANETs) have been recognized by governmental organizations and vehicle manufacturers [1]. VANET is a special type of mobile ad hoc network, and is characterized by several properties: (i) nodes move at high speeds, which results in frequent and fast network topology changes; (ii) the topology and the node movement are constrained by roads, and mobility is restricted by traffic regulations, such as speed limit; (iv) energy consumption is not an issue, and vehicles can provide continuous power to the communication devices

In VANETs, data messages can be transmitted among a large scale of vehicles in a very short time. Consequently, there are many safety related applications that can be carried out. Moreover, VANETs technologies have the potential to address forward collisions, lane change or merging and intersection collisions. Besides the safety related applications, many information service applications can be carried out in VANETs, as advertising or traffic control and optimization.

To minimize the influence of network topology change and reduce the redundant flooding in ad hoc networks, many clustering schemes have been proposed [2]. The main idea of clustering routing scheme is to dynamically organize all mobile nodes into groups called *clusters*, while these clusters choose a set of nodes as cluster heads (CHs). The optimal CH selection is inherently an NP-hard problem. In addition, it is worth noting CH election is extremely challenging in VANETs due to frequent topology changes. Some existing solutions to this problem are based on heuristic policies [3], such as based on the identifier, degree, energy level, position, speed and direction. According to these approaches, a node is chosen to be a CH if its weight is higher than any of its neighbours' weights; otherwise, it joins a neighbouring CH.

In this paper, an alternative clustering approach is proposed based on a specific application of coalitional game theory, where networking is performed in an ad hoc basis to pursue full context awareness of vehicles. Specifically, the proposed approach relies upon the setting up of cluster as soon as convoys arise in traffic dynamics, and in dynamically reacting to topology changes (i.e., convoys *joining* or *leaving*). This approach is capable to manage both communications within the same cluster and between adjacent clusters, across different nodes spatial deployments and mobility patterns (i.e., urban and highway scenarios).

The paper is organized as it follows. In Sec. II an overview on clustering techniques literature is proposed, while the proposed protocol is introduced in Sec. III, by properly defining a utility function for each node under the hypothesis depending on their possible roles. In addition, the underlying communications protocol is characterized in terms of exchanged messages. Further, in Sec. IV the proposed protocol performance is evaluated for different operative scenarios, always pointing out that a coalitional game outperforms a selfish approach whenever the nodes spatial deployment and mobility patterns are concerned. Finally, conclusions are drawn in Sec. V.

II. Related Works

The research interests in the area of VANET communications witness a durable increase over the last decade. In particular, the relation between the topology control via game theory represent an open issue. In [4], the coalitional games are classified into three classes: canonical coalitional games, coalition formation games, and coalitional graph games. This represents an application-oriented approach for understanding and analysing coalitional games. The specific aspect of VANET has been addressed by [5]. Regarding the communication between distinct clusters, we refer to [6], where the communications between cluster heads in the presence of the time constraint (mainly related to vehicle speed) are analysed.

Clustering represents a technique widely adopted in ad hoc wireless systems to group together *homogeneous* nodes and ease network management. Clustering schemes are usually based on the following approaches [7]:

- *Bottom-Up*: according to this, pre-existing clusters are iteratively joined together till the number of clusters reach a minimum value;
- *Top-Down*: nodes are initially grouped in a unique cluster which is partitioned into more homogeneous sub-clusters till a maximum number of clusters is reached.

Clustering schemes can be further classified in [8]:

- *Hard* clustering: a node exclusively belongs only to a cluster; and thus no overlapping is allowed.
- *Soft* clustering, a node might be associated to several clusters with different affinity degrees.

Another taxonomy might relays on the adopted space partitioning algorithm [9]; in particular we have:

- *Partitioned* clustering: after establishing the maximum number of possible groups, a node is assigned to a particular group depending on the value of the distance towards a reference element of each group;
- *Hierarchical* clustering: where partitions are arranged in increasing or decreasing subsets represented with a tree structure with the associated (un)grouping rules.

Some clustering approaches, such as the Lowest-ID (LID) [10], focus on maximising network connectivity using as CH election metrics the *generalized distance*, without considering the residual energy of each node. Another class of algorithms aims at simplifying the whole election process by lowering the beacon and signalling messages overhead. This kind of schemes are mainly based on probabilistic rules and are characterized by low complexity, making the network quite reactive and allowing a uniform energy consumption. Among them, the most famous scheme is the well known LEACH (Low Energy Adaptive Clustering Hierarchy) protocol [11] that relies on a randomized CH turn over. Each node independently generates a random number $\psi \in [0, 1]$. Then, if the node has not been a CH in the last $1/P$ rounds[1], where P is the average percentage of expected CHs, a threshold ψ^*, such that $\psi^* \doteq \frac{P}{1-P\left[n_r \bmod (1/P)\right]}$ is introduced, where n_r represents the number of rounds since the node has been elected as CH. If $\psi < \psi^*$, the node declares itself as CH. Furthermore, nodes that have been CH in the initial round cannot be elected again for the next $\lceil 1/P \rceil$ rounds. Therefore, this technique allows to achieve a more balanced energy consumption among the nodes and a longer network lifetime. However, the LEACH protocol does not take into account node residual energy and does not provide proper adaptation to different deployment scenarios, often leading to suboptimal network configurations. Due to random CH placement, this approach tends to make configurations with non-uniform CH density across the covered area and unbalanced load among the CHs.

In designing our approach, we adopted a top-down, hard and partitioned clustering scheme, where a node is allowed to selected another cluster head if the operative conditions vary. In addition, we compare the achieved performance with an hybrid scheme in which the CHs selection is performed according to the LEACH scheme.

III. Proposed Approach

A. Reference Scenario

VANETs play a crucial role for driving safety and traffic management in both urban and extra-urban scenarios. Communication takes place either among On Board Units (OBUs) and Road Side Units (RSUs), or only among OBUs. Vehicle-to-Vehicle (V2V) is a potential solution to exchange context information allowing data fusion and dissemination among vehicles. For example, vehicles in urban scenarios typically gather in convoys with highly correlated speed. This situation leads to consider the possibility of *spontaneous* clustering, headed by a CH, where vehicles might exchange context information about road conditions or driving safety information [12]. This requires efficient and robust protocols to manage both *intra* and *inter* clusters communications [13]. A certain degree of cooperation among involved potential nodes is beneficial to establish effective communication and share knowledge (or reliable estimation) of the system status. Here we assume that data are periodically refreshed[1].

B. Payoff Characterization

In characterizing our model, we consider only OBUs, i.e., communications are exclusively V2V. We assume three types of nodes:

- Ordinary Node (ON): it sends data toward the CH and receives processed information from the CH;
- CH: it gathers information from all the ONs in its domain, performs data fusion and then disseminates *local* context information to the ONs;
- Free Node (FN): it represents a node that is not a CH or associated to a CH.

The joint utility function $U_{i,j}$, when considering a couple of nodes i, j, depends on $\mathcal{G}$. In defining $U_{i,j}$, it is necessary to take into account the role assumed by each node, i.e., ON, CH or FN.

1) ON Payoff: The utility function of the i-th node, under the hypothesis that it is an ON associated with CH j, takes into account both benefit and cost. The context related information received by its CH is beneficial for the ON, while the sensed data sent to the CH represents a cost. As a results, the utility can be expressed as:

$$U_{i,j} \doteq P_{i,j}\, \varepsilon_j - C_{tx}^{ON} \tag{1}$$

where $P_{j,i}$ is the probability that the transmission from the j-th CH to the i-th ON occurs successfully, ε_j is the *effective information rate* of the j-th node (CH), and C_{tx}^{ON} is the cost function for updating the sensed information, assumed to be equal for all the ONs. The *useful rate* of information which can be delivered, and depends both on information rate λ_i of

[1]According to IEEE 802.11p, vehicles are allowed to share their GPS related position together with speed and acceleration [14].

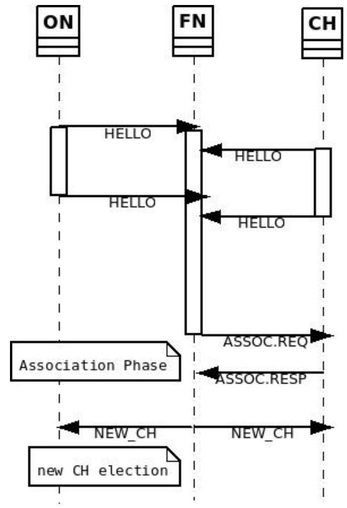

Fig. 1. Sequence diagram of the proposed protocol: (i) joining and (ii) new CH election phases.

the i-th node and the compression factor ψ_i. It can be defined as follows:

$$\varepsilon_j \doteq \sum_{i=1}^{\delta_i} \lambda_i \psi_i \, T_{cl} \tag{2}$$

where δ_j represents the estimated connectivity degree, which is the number of ONs in the same cluster associated with the j-th node (CH) over the cluster coherence time T_{cl},

2) CH Payoff: In order to be elected as a CH, the generic j-th node might have a payoff U_j (under the hypothesis of being a CH) greater than that one of being an ON or a FN. It is worth noticing that for FN the payoff has been assumed equal to zero. Specifically, U_j can be characterized as:

$$U_j \doteq \sum_{i=1}^{\delta_j} P_{i,j} \, \lambda_i \psi_i - C_{tx}^{CH} - C_{pr}^{CH} \tag{3}$$

where C_{tx}^{CH} is the cost for data transmission, and C_{pr}^{CH} is related to the processing cost by the CH over all the received data.

C. Proposed Protocol Characterization

In the following the proposed protocol is characterized; in particular, the following phases have been addressed:

- *Joining*: a disconnected nodes is associating as ON with a specific CH;
- *Leaving*: a node (ON or CH) leaves the cluster;
- *New CH election*: an ON is elected as the CH.

In Fig. 1, the sequence diagram of the proposed protocol is depicted for what the (i) joining and (ii) new CH election phases are concerned.

1) Joining: It has been adopted a *join and leave* approach. i.e., with a gradual network set-up. Specifically, it is supposed that a cluster has been already established, where only ONs might vary. The focus here is on a single admission request performed by a node not belonging to the cluster. According to the proposed protocol design, every node periodically sends a `HELLO` to notify the neighbours with its status. This message is comprised with the following fields:

- `SendID`: the sender address;
- `Info`: the information rate associated with this node;
- `Type`: it could be CH, ON, or FN;
- `RecID`: that is in this case the broadcast address.

The incoming node upon collecting a certain number of `HELLO` messages (i.e., after a proper timeout expiring) updates its payoff, and depending on its value, requests its association to the best CH candidate though the `ASSOCIATION.REQ` message; as the CH accepts the requesting node, it adds the node to associated ONs list and sends to it an `ACK` message.

2) Leaving: When an ON decides to leave a cluster, first it changes its `type` from ON to FN and notifies this variation in the next `HELLO` message and its CH can remove it from the associated ONs list.

3) New CH election: In this case, an incoming FN joins a cluster as a new CH. The messages exchange is similar to the first case, but the incoming node broadcasts a `NEWCH` message (instead of `ASSOCIATION.REQ` message) with the following fields:

- `SendID`: the sender address;
- `Info`: the information rate associated with this node;
- `Type`: in this case CH;
- `RecBroad`: broadcasting receiving address.

It is worth noticing that the value of the `Info` field is extremely relevant for the FNs coming from the opposite direction with respect to the cluster to be associated or not.

IV. Performance Analysis

A. Reference Scenarios

In performing the numerical simulations, it has been considered the following scenarios:

1) *Manhattan Grid*: this represents a typical urban scenario in which nodes are disposed in a grid fashion at a fixed distance D ($25m \leq D \leq 75m$).
2) *Highway*: it models an highway scenario with different lanes and two opposite directions, with nodes arranged in convoys moving with an average speed.

The clustering approaches hereinafter considered are:

- *Selfish*, where each node elects itself as the CH or ON independently from each other and based on *local* payoff maximization.
- *Selfish LEACH*, according to which the CH selection is performed according to the LEACH algorithm [11], while the decision upon being an ON or FN is based on the payoff maximization.
- *Coalitional* game, where node that has the greater utility function is elected as the CH, while the remaining nodes decide whether to be associated with this CH or not[2].

Depending on the reference scenario, the previous clustering strategies are compared.

[2]This policy has been made possible thank to an improved communications protocols among nodes, with an increased overhead, which has not been analysed.

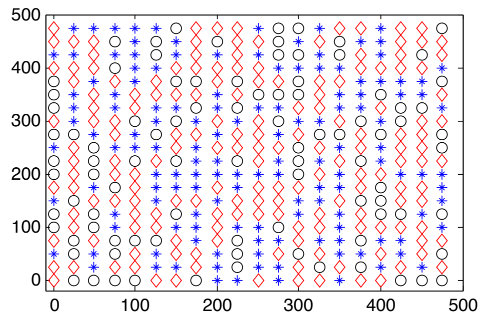

Fig. 2. Achieved network topology for a selfish clustering approach and Manhattan Grid deployment with $N = 400$, $D = 25m$: CHs, ONs and FNs are referred to as blue stars, red diamonds and black circles, respectively.

TABLE I
PERFORMANCE OF A SELFISH CLUSTERING APPROACH AND MANHATTAN GRID DEPLOYMENT WITH $N = 400$, D=25.

Range	CH	ON	FN	MeanON
75	38%	37%	25%	0.97
50	38%	37%	25%	0.97
25	38%	37%	25%	0.97

B. Numerical Results

1) Manhattan Grid: In Fig. 2, it is sketched a typical network topology achieved by a selfish clustering approach, while in Tab. III, the performance is shown as a function of the coverage range. It can be noticed the high CHs (38%) and FNs (25%) percentages, due to a scarce information exchange among nodes leading to a low degree of cooperation and cluster size of 1.028 ONs. As a consequence, when a selfish clustering approach is adopted, the achieved performance is suboptimal. In addition, it can be noticed that the performance is not affected by the coverage range R and the curve is flat. When adopting an hybrid selfish LEACH scheme with $P = 0.1$, i.e., a CH target percentage a priori fixed, the performance gets increases, as indicated in Tab. II, even thought the percentage of FNs is not negligible, regardless of the coverage radius.

If a coalition clustering approach is adopted, the achieved topology is more clustered as shown in Fig. 3. Moreover, the performance is remarkably increased as highlighted in Tab. III, in particular for $R = 75m$ it can be noticed that: (i) FNs percentage is negligible (0.25%), (ii) CHs percentage is reduced (6.25%) thanks to a higher degree of cooperation among nodes, (iii) a higher cluster size (14.96 ONs per CH).

TABLE II
PERFORMANCE OF A SELFISH LEACH CLUSTERING APPROACH AND MANHATTAN GRID DEPLOYMENT WITH $N = 400$, D=25, $P = 0.1$.

Range	CH	ON	FN	MeanON
75	10%	46.5%	43.5%	4.65
50	10%	46.5%	43.5%	4.65
25	10%	46.5%	43.5%	4.65

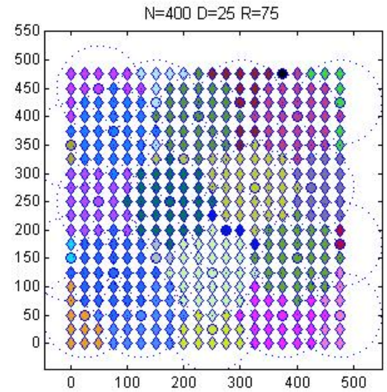

Fig. 3. Achieved network topology for a coalitional clustering approach and Manhattan Grid deployment with $N = 400$, $D = 25m$: the clusters are depicted in different colors.

TABLE III
PERFORMANCE OF A COALITIONAL CLUSTERING APPROACH AND MANHATTAN GRID DEPLOYMENT WITH $N = 400$, D=25.

Range	CH	ON	FN	MeanON
75	6.25%	93.50%	0.25%	14.96
50	11.25%	87.75%	1%	7.80
25	20.25%	69%	10.75%	3.41

2) Highway: In this scenario, a highway segment comprised of four lanes and two opposite convoys of 60 nodes each (forming two clusters) has been considered. The performance achieved by a selfish approach has been described in Tab. IV, and it is quite close to the Manhattan grid scenario. In addition, the key figures of the hybrid selfish LEACH protocol have been presented with $P = 0.1$ which is able to increase the cluster size, even though the FN percentage increases as well.

When a coalitional approach is adopted, as soon as the convoys get closer the cluster with higher effective information rate attracts ONs from the other one till a kind of *large* coalition is achieved. In this situation, where 96.7%[3] are clustered together, no FN is present and a full context awareness is achieved.

In Figs. 4-5 the selfish and coalitional policies are compared. We notice that for a selfish approach FN percentage is greater than 20%, and the CH and ON percentages are excessive and

[3]The remaining nodes are not clustered due to geometric effects.

TABLE IV
PERFORMANCE FOR A SELFISH (OR SELFISH LEACH) CLUSTERING APPROACH AND HIGHWAY DEPLOYMENT FOR 6 CONSECUTIVE ELECTION ROUNDS.

Round	CH	ON	FN
1	33.3% (10%)	42.5% (46.7%)	24.2% (43.3%)
2	45% (10%)	28.3% (42.5%)	26.7% (47.5%)
3	42.5% (10%)	31.7% (36.7%)	25.8% (53.3%)
4	38.3% (10%)	37.5% (51%)	24.2% (39%)
5	34.2% (10%)	44.2% (46.7%)	21.7% (43.3%)
6	38.3% (10%)	39.2% (35.5%)	22.5% (55.5%)

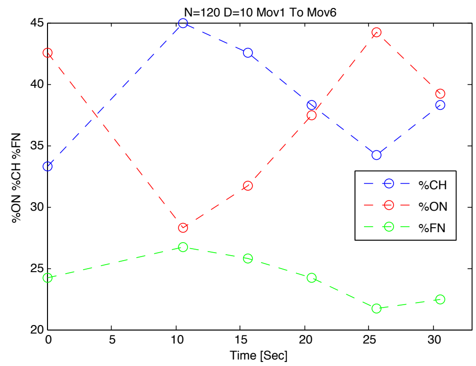

Fig. 4. Performance for a selfish clustering approach and Highway deployment as a function of time.

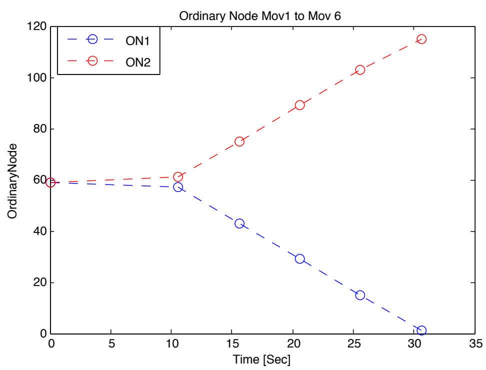

Fig. 5. ONs percentages for convoys 1 and 2 for a coalitional clustering approach and Highway deployment as a function of time.

oscillate with time, while for a coalitional approach, a constant ONs migration from Cluster 1 towards Cluster 2 (which has the higher effective information rate) can be highlighted, thus originating a *large* coalition.

V. Conclusions

To minimise the influence of VANET network topology changes, we focus on a clustering scheme, which dynamically organizes all mobile nodes into groups (i.e., clusters). The proposed approach relies upon the setting up of clusters as soon as convoys arise in traffic dynamics, or they merge or separate each other. This allows to pursue full context awareness of vehicles.

Being the optimal CH selection inherently an NP-hard problem, extremely challenging due to frequent topology changes, we propose an alternative clustering approach based on a specific application of coalitional game theory.

First, we define a utility function for each node under the hypothesis of being an ordinary node, cluster head or free node. In addition, the underlying communication protocol is characterized in terms of exchanged messages. Then, the proposed protocol performance is evaluated for several operative scenarios with different nodes spatial deployment and mobility patterns, always pointing out that a coalitional game outperforms a selfish approach. In particular, for a Manhattan Grid urban scenario, the proposed approach allows almost all nodes to be always clustered with a percentage of CH approximately equal 10% for practical values of the coverage range. A Highway scenario has been also investigated to point out the reactiveness of our protocol in the case of clusters joining, where a large coalition is originated.

References

[1] D. Tian, Y. Wang, H. Xia, and F. Cai, "Clustering multi-hop information dissemination method in vehicular ad hoc networks," *Intelligent Transport Systems, IET*, vol. 7, no. 4, pp. 464–472, Dec. 2013.

[2] D. Wei and H. Chan, "Clustering ad hoc networks: Schemes and classifications," in *Sensor and Ad Hoc Communications and Networks, 2006. SECON '06. 2006 3rd Annual IEEE Communications Society on*, vol. 3, Sep. 2006, pp. 920–926.

[3] J. Yu and P. Chong, "A survey of clustering schemes for mobile ad hoc networks," *Communications Surveys Tutorials, IEEE*, vol. 7, no. 1, pp. 32–48, f quarter 2005.

[4] W. Saad, Z. Han, M. Debbah, A. Hjorungnes, and T. Basar, "Coalitional game theory for communication networks," *Signal Processing Magazine, IEEE*, vol. 26, no. 5, pp. 77–97, Sep. 2009.

[5] T. Wang, L. Song, and Z. Han, "Coalitional graph games for popular content distribution in cognitive radio vanets," *Vehicular Technology, IEEE Transactions on*, vol. 62, no. 8, pp. 4010–4019, Oct. 2013.

[6] W. Saad, Z. Han, T. Basar, M. Debbah, and A. Hjorungnes, "Hedonic coalition formation for distributed task allocation among wireless agents," *Mobile Computing, IEEE Transactions on*, vol. 10, no. 9, pp. 1327–1344, Sep. 2011.

[7] M. Srinivas and C. Mohan, "Efficient clustering approach using incremental and hierarchical clustering methods," in *Neural Networks (IJCNN), The 2010 International Joint Conference on*, Barcelona, Spain, July 2010.

[8] A. Subramanian and A. Sayed, "Resource allocation strategies for wireless ad-hoc networks," in *Acoustics, Speech, and Signal Processing, 2004. Proceedings. (ICASSP '04). IEEE International Conference on*, vol. 4, May 2004, pp. iv–569–iv–572 vol.4.

[9] J. Ghaderi, L.-L. Xie, and X. Shen, "Hierarchical cooperation in ad hoc networks: Optimal clustering and achievable throughput," *Information Theory, IEEE Transactions on*, vol. 55, no. 8, pp. 3425–3436, Aug 2009.

[10] M. Gerla and J. T.-C. Tsai, "Multicluster, mobile, multimedia radio network," *Wirel. Netw.*, vol. 1, pp. 255–265, Aug. 1995.

[11] W. Heinzelman, A. Chandrakasan, and H. Balakrishnan, "Energy-efficient communication protocol for wireless microsensor networks," in *System Sciences, 2000. Proceedings of the 33rd Annual Hawaii International Conference on*, Honolulu, Hawaii, Jan. 2000.

[12] F. Chiti, R. Fantacci, and R. Mastandrea, "A low complexity clustering approach enabling context awareness in sparse vanets," in *Global Communications Conference (GLOBECOM), 2012 IEEE*, Atlanta, Georgia, Dec 2012.

[13] F. Chiti, R. Fantacci, and G. Rigazzi, "A mobility driven joint clustering and relay selection for ieee 802.11p/wave vehicular networks," in *Communications (ICC), 2014 IEEE International Conference on*, Sydney, Australia, Jun. 2014.

[14] "IEEE standard for information technology– local and metropolitan area networks– specific requirements– part 11: Wireless lan medium access control (mac) and physical layer (phy) specifications amendment 6: Wireless access in vehicular environments," *IEEE Std 802.11p-2010 (Amendment to IEEE Std 802.11-2007 as amended by IEEE Std 802.11k-2008, IEEE Std 802.11r-2008, IEEE Std 802.11y-2008, IEEE Std 802.11n-2009, and IEEE Std 802.11w-2009)*, pp. 1–51, July 2010.