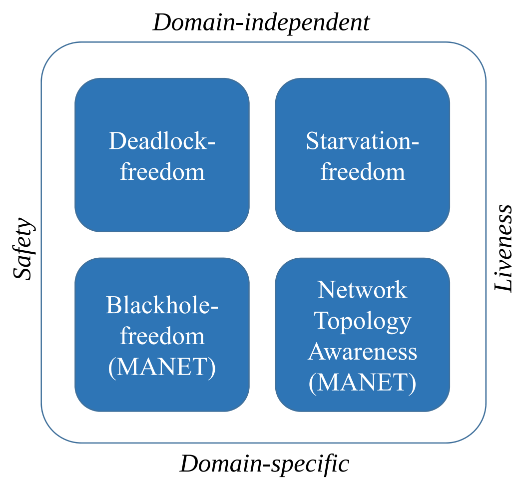
# I protocolli N-AODV e B-AODV per MANET

## Nota Preliminare

- La presente dispensa è una rivisitazione di uno dei seminari tenuti dal Dr. Gennaro Vessio per l'a.a. 2016-17, completato con considerazioni svolte negli articoli
  - Bianchi A., Pizzutilo S., Vessio G. Preliminary Description of NACK-based Ad-hoc On-demand Distance Vector Routing Protocol for MANETs. In: 9th International Conference on Software Engineering and Applications (ICSOFT-EA 2014), Vienna, Austria, pp. 500-505, SciTePress, 2014
  - Bianchi A., Pizzutilo S., Vessio G. Comparing AODV and N-AODV Routing Protocols for Mobile Ad-hoc Networks. In: 13th International Conference on Advances in Mobile Computing and Multimedia (MoMM 2015), Brussels, Belgium, pp. 159-168, Association for Computing Machinery, 2015
  - Bianchi A., Pizzutilo S., Vessio G. CoreASM-based Evaluation of the N-AODV Protocol for Mobile Ad-hoc Networks. Journal of Mobile Multimedia, 12(1-2), pp. 31-51, Rinton Press, 2016
  - Bianchi A., Pizzutilo S., Vessio G., Intercepting Blackhole Attacks in MANETs: An ASM-based Model, Proc. of the 1st International Workshop on Formal Approaches for Advanced Computing Systems – FAACS2017, Trento - Italy, September 2017, to appear



## Classi di proprietà






## Le MANET

- Una rete mobile ad-hoc (MANET) è una rete wireless caratterizzata da:
  - Assenza di infrastruttura fisica fissa
  - Topologia dinamica
- Specifici protocolli di routing si basano sulla cooperazione fra più host per stabilire route fra coppie di end-point:
  - Proattivi
  - Reattivi
  - Ibridi

# Network Topology Awareness

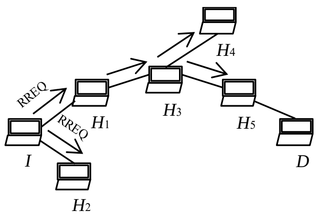


# Concetto generale

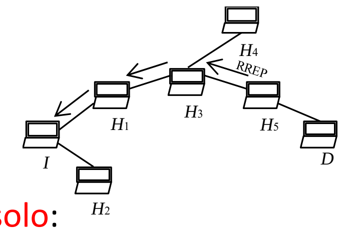
- La network topology awareness (NTA) si riferisce alla conoscenza che ciascun host ha:
  - Degli altri host
  - Della loro raggiungibilità attraverso una route
- Tale aspetto è importante in svariate applicazioni:
  - Algoritmi di elezione del leader
  - Sicurezza
  - VANET
  - …
- *Come varia la NTA in funzione del protocollo di routing adottato?*



# Limiti di AODV




RREQs are broadcasted

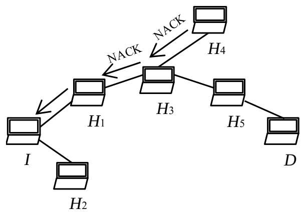



An RREP is unicasted

- In AODV ogni nodo conosce solo:
  - I suoi vicini
  - Il prossimo nodo nel percorso verso nodi non vicini
- *Come migliorare tale aspetto?*



# NACK-based AODV (N-AODV)




NACKs are unicasted

- Ogni nodo intermedio che ignora come raggiungere la destinazione comunica all'iniziatore del route discovery che «non sa nulla!»

# Modellazione in ASM

- Una MANET che adotta N-AODV può essere modellata da una DASM composta di $Hosts = \{h_1, \ldots, h_n\}$
- Ogni ASM $h_i$ è caratterizzata da:
  - $neighb$: $Hosts \to \mathrm{PowerSet}(Hosts)$
  - $wishToInitiate$: $Hosts \times Hosts \to boolean$
  - Tre code di pacchetti
  - Una tabella di routing



# Host program

```
HostProgram(h_i) =
if ¬isEmpty(requests(self)) then {
  RREQ := top(requests(self))
  previousHop := sender of RREQ
  UpdateRoutingTable(self, RREQ)
  Router(RREQ, previousHop)
  dequeue RREQ from requests(self)
}
if wishToInitiate(self, dest) = true then
  Initiator(dest)

if ¬isEmpty(nacks(self)) then {
  NACK := top(nacks(self))
  if NACK.dest ≠ self then {
    previousHop := select r.nextHop ∈
      routingTable(self) with
        r.dest = NACK.dest
    UpdateRoutingTable(self, NACK)
    enqueue NACK into nacks(previousHop)
    dequeue NACK from nacks(self)
  }
}

if ¬isEmpty(replies(self)) then {
  RREP := top(replies(self))
  if RREP.init ≠ self then {
    previousHop := select r.nextHop ∈
      routingTable(self) with
        r.dest = RREP.init
    UpdateRoutingTable(self, RREP)
    enqueue RREP into replies(previousHop)
    dequeue RREP from replies(self)
  }
}
```



# Predicati sugli stati

- Ciascuna ASM può trovarsi in uno fra più stati computazionali ciascuno caratterizzato da uno o più predicati sugli stati:
  - idle
  - routing
  - initiating
  - forwarding
- Per esempio, forwarding = $isEmpty(replies(\mathbf{self})) = false \lor isEmpty(nacks(\mathbf{self})) = false$



# Correttezza

**Theorem.** *The route discovery process always ends*

*Sketch of proof.* Each ASM can enter four different computational branches depending on which rule is executed. Every time a computational branch is entered the computation is reversible to the initial state. Therefore, the thesis holds □

# Esperimento

- *Come si comporta N-AODV rispetto ad AODV?*
- Quesiti di ricerca:
  - Quale protocollo esibisce maggiore NTA?
  - Qual è il più efficace?
  - E il più efficiente?
- Metodo: simulazioni
- Tool: CoreASM
- Modello di mobilità: topology-based
- Parametri:
  - Dimensione della rete: 10, 25, 50 host
  - Livello di mobilità: alta, bassa
  - Numero di run: 500



# Metriche

- Network Topology Awareness:
  - Routing tables size
  - Routing tables updates
  - Network awareness lag
  - Broadcast activations
- Efficacia:
  - Total rate of success
- Efficienza:
  - Control overhead



# Formulazione delle ipotesi

- Per ogni metrica concernente NTA ed efficienza:
  - $H_0$: non c'è differenza statisticamente significativa fra i due protocolli
  - $H_1$: c'è differenza statisticamente significativa fra i due protocolli
- I valori relativi al total rate of success, invece, sono semplicemente confrontati



# Risultati: Routing tables size

| Scenario | AODV (media) | N-AODV (media) | p-value |
|---|---|---|---|
| 10 host/Alta mobilità | 13.092 | 21.13 | < 0.0001 |
| 10 host/Bassa mobilità | 25.772 | 28.544 | < 0.0001 |
| 25 host/Alta mobilità | 129.948 | 164.78 | < 0.0001 |
| 25 host/Bassa mobilità | 182.272 | 225.424 | < 0.0001 |
| 50 host/Alta mobilità | 575.566 | 809.966 | < 0.0001 |
| 50 host/Bassa mobilità | 1030.224 | 1135.414 | < 0.0001 |

# Risultati: Routing tables updates

| Scenario | AODV (media) | N-AODV (media) | p-value |
|---|---|---|---|
| 10 host/Alta mobilità | 0.912 | 1.236 | 0.5661 |
| 10 host/Bassa mobilità | 0.52 | 0.878 | 0.0016 |
| 25 host/Alta mobilità | 3.404 | 5.182 | 0.0106 |
| 25 host/Bassa mobilità | 2.202 | 3.46 | 0.0413 |
| 50 host/Alta mobilità | 9.598 | 13.158 | 0.5598 |
| 50 host/Bassa mobilità | 6.556 | 8.056 | 0.0369 |



# Risultati: Network awareness lag

| Scenario | AODV (media) | N-AODV (media) | p-value |
|---|---|---|---|
| 10 host/Alta mobilità | 6.103 | 2.6136 | < 0.0001 |
| 10 host/Bassa mobilità | 5.3769 | 2.8883 | < 0.0001 |
| 25 host/Alta mobilità | 3.8867 | 2.2163 | < 0.0001 |
| 25 host/Bassa mobilità | 3.3082 | 1.5847 | < 0.0001 |
| 50 host/Alta mobilità | 2.2764 | 1.047 | < 0.0001 |
| 50 host/Bassa mobilità | 1.5191 | 1.1705 | < 0.0001 |



# Risultati: Broadcast activations

| Scenario | AODV (media) | N-AODV (media) | p-value |
|---|---|---|---|
| 10 host/Alta mobilità | 1.914 | 1.446 | 0.0002 |
| 10 host/Bassa mobilità | 1.104 | 1.03 | 0.5848 |
| 25 host/Alta mobilità | 4.24 | 3.052 | 0.0022 |
| 25 host/Bassa mobilità | 2.722 | 2.226 | 0.0088 |
| 50 host/Alta mobilità | 11.376 | 5.496 | < 0.0001 |
| 50 host/Bassa mobilità | 7.972 | 3.414 | < 0.0001 |



# Risultati: Total rate of success

| Scenario | AODV (%) | N-AODV (%) |
|---|---|---|
| 10 host/Alta mobilità | 61.6 | 69 |
| 10 host/Bassa mobilità | 66.8 | 71.2 |
| 25 host/Alta mobilità | 71 | 76 |
| 25 host/Bassa mobilità | 71.4 | 82.4 |
| 50 host/Alta mobilità | 78.2 | 80.6 |
| 50 host/Bassa mobilità | 85.4 | 90 |

## Risultati: Control overhead

| Scenario | AODV (media) | N-AODV (media) | p-value |
|---|---|---|---|
| 10 host/Alta mobilità | 1.07 | 1.32 | 0.6268 |
| 10 host/Bassa mobilità | 1.05 | 1.27 | 0.3857 |
| 25 host/Alta mobilità | 4.8 | 5.4 | 0.6457 |
| 25 host/Bassa mobilità | 5.16 | 6.97 | 0.2728 |
| 50 host/Alta mobilità | 11.15 | 10.768 | 0.0898 |
| 50 host/Bassa mobilità | 8.846 | 7.74 | 0.4286 |



## Analisi

- N-AODV:
  - Fornisce agli host maggiore NTA rispetto ad AODV
  - È più efficace
  - Non è meno efficiente
- L'esperimento condotto soffre di minacce alla validità. *Quali?*



## Blackhole-freedom



## BACKGROUND

## The context

- A Mobile Ad-hoc NETwork (MANET) is a network designed for wireless communications among mobile hosts:
  - It lacks of a fixed infrastructure
  - Hosts act both as initiator/destination and as intermediate router
  - Each host must be able to read all pcks for routing them to destination
- The intrinsic features of MANET make them vulnerable to security attacks
  - We focus on blackhole attack



## Blackhole

- A blackhole is a malicious host in the network that sends fake routing information
- It claims to know the best route to reach a destination
  - Pcks are so routed to it
  - It can then misuse or discard them
- Sometimes there are several malicious hosts
  - the attack is cooperatively executed by the main blackhole and its colluders
- A Greyhole is a blackhole that alternates malicious and honest behaviour in an unpredictable way
  - Here we don't consider greyholes



## Our research

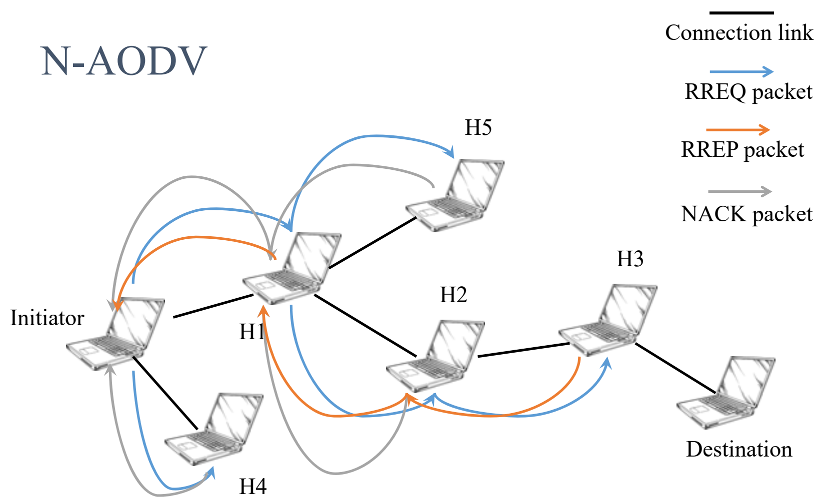
- Formal specification of Blackhole-free N-AODV routing protocol – BN-AODV
  - The Ad-hoc On-demand Distance Vector (AODV) protocol is one of the most popular routing protocol for MANETs (*)
  - We proposed a variant of the protocol: the NACK-based AODV (N-AODV) (#); it improves the network topology awareness (°)
  - We now enrich N-AODV with the capability to intercept blackholes
- The protocol is formally specified by means of Abstract State Machines (ASMs)

(*) C.E. Perkins et al. http://tools.ietf.org/html/rfc3561 (2003)
(#) A. Bianchi et al. Preliminary Description of NACK-based AODV for MANETs. ICSOFT (2014)
(°) A. Bianchi et al. CoreASM-based Evaluation of the N-AODV Protocol for Mobile Ad-hoc NETworks. J. of Mobile Multimedia, (2016)



# Blackhole-free N-AODV

# N-AODV





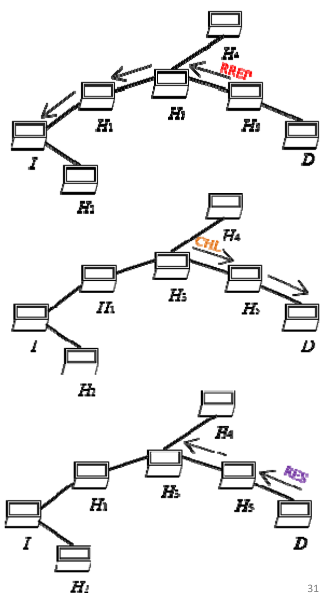

# BN-AODV (1/2)

- The main idea is that each host receiving an RREP must verify the trustworthiness of the next host to dest
- It adds two control pcks:
  - Challenge (CHL) – is an encrypted nonce to be decremented by the destination
  - Response (RES) – is the encrypted decremented value



# BN-AODV (2/2)

- $H_3$ receives an RREP from $H_5$
- $H_3$ unicasts CHL to D through $H_5$
  - If $H_3$ receives back the correct RES, then $H_5$ is considered trusted
  - Else $H_5$ is considered a blackhole






# ASM model of BN-AODV

## Generality

- The MANET is modeled by a DASM, including a set of Hosts={$h_1$, $h_2$, …, $h_n$}
  - each $h_i$ models the behavior of the i-th host executing the protocol
- Each host behaves either as an honest node, or as a blackhole, or as a colluder
  - No greyhole
- Three ASMs describe the three different cases



## Honest ASM - HostProgram

```
if ¬isEmpty(requests(self)) then {
 let RREQ = top(requests(self)), previousHop = RREQ.sender in
  UpdateRoutingTable(self, RREQ)
  Router(RREQ, previousHop)
  dequeue RREQ from requests(self)
}
if wishToInitiate(self) = true then
 forall dest ∈ Hosts with dest ≠ self do
  if initiateTo(self, dest) = true then
   Initiator(dest)
if ¬isEmpty(replies(self)) then
 let RREP = top(replies(self)), nextHop = RREP.sender in
  if RREP.init ≠ self then {
   choose entry ∈ routingTable(self) with entry.dest = RREP.init
   previousHop := entry.nextHop seq
   hasToVerify(previousHop, nextHop, RREP.dest):=true
  }
forall previousHop ∈ neighb(self) do
 forall nextHop ∈ neighb(self) do
  forall dest ∈ Hosts do
   if hasToVerify(previousHop, nextHop, dest) then
    Verify(top(replies(self)), previousHop, nextHop, dest)
if ¬isEmpty(responses(self)) then {
 let RES = top(responses(self)) in
  if RES.dest ≠ self then {
```

```
if ¬isEmpty(challenges(self)) then {
  let CHL = top(challenges(self)) in
   if CHL.dest = self then {
    let previousHop = CHL.sender in
     create_RES seq
     enqueue RES into responses(previousHop)
     dequeue CHL from challenges(self)
   }
   if CHL.dest ≠ self then {
    choose entry ∈ routingTable(self) with entry.dest = CHL.dest
    nextHop := entry.nextHop seq
    enqueue CHL into challenges(nextHop)
    dequeue CHL from challenges(self)
   }
 }
if ¬isEmpty(nacks(self)) then {
  let NACK = top(nacks(self)) in
   if NACK.dest ≠ self then {
    choose entry ∈ routingTable(self) with entry.dest = NACK.dest
    previousHop := entry.nextHop seq
    UpdateRoutingTable(self, NACK)
    enqueue NACK into nacks(previousHop)
    dequeue NACK from nacks(self)
   }
 }
```



## Honest ASM - Initiator

```
if dest ∈ neighb(self) ∨ dest ∈ routingTable(self) then {
  CommunicationSession(dest)
  initiateTo(self, dest) := false
 }
 if dest ∉ neighb(self) ∧ dest ∉ routingTable(self) then {
  create_RREQ seq
  BroadcastRREQ(RREQ)
  initiator_waiting(self, dest) := true
  initiator_timeout(self, dest) := default_value
 }
 if initiator_waiting(self, dest) then
initiator_timeout(self,dest):=initiator_timeout(self,dest)
−1 seq
   if ¬isEmpty(replies(self)) then
    forall r∈replies(self) with r.init=self and r.dest =dest
do
     if trusted(self, dest) = undef then
      let nextHop = r.sender in Verify(r, null, nextHop,
dest)
```

```
if trusted(self, dest) then {
  CommunicationSession(dest)
  initiateTo(self, dest) := false
  initiator_waiting(self, dest) := false
}
if initiator_waiting(self, dest) ∧
¬isEmpty(nacks(self)) then {
  forall n ∈ nacks(self) with n.dest = self do {
   UpdateRoutingTable(self, n)
   dequeue n from nacks(self)
  }
}
if initiator_waiting(self, dest) ∧
initiator_timeout(self, dest)=0
then {
  initiateTo(self, dest) := false
  initiator_waiting(self, dest) := false
}
```



## Honest ASM - Verify

```
if ¬verify_waiting(self, dest) then {
  create_CHL seq
  enqueue CHL into challenges(nextHop)
  verify_waiting(self, dest) := true
  verify_timeout(self, dest) := default_value
 }
 if verify_waiting(self, dest) then {
  if ¬isEmpty(responses(self)) then
   if ReliableRREP(self, top(responses(self))) then {
    trusted(self, dest) := true
    verify_waiting(self, dest) := false
    dequeue top(responses(self)) from
responses(self)
   }
  verify_timeout(self, dest) := verify_timeout(self,
dest) – 1
 }
```

```
 if verify_waiting(self, dest)∧verify_timeout(self,
dest) =0 then {
  trusted(self, dest) := false
  verify_waiting(self, dest) := false
 }
 if trusted(self, dest) then {
  UpdateRoutingTable(self, RREP)
  UpdateTrustTable(self, nextHop)
  dequeue RREP from replies(self)
  if previousHop ≠ null then
   enqueue RREP into replies(previousHop)
 }
 if ¬trusted(self, dest) then {
  UpdateTrustTable(self, nextHop)
  dequeue RREP from replies(self)
 }
```

## Malicious ASM - Blackhole Program

**if** ¬isEmpty(requests(**self**)) **then** {
  **let** RREQ = top(requests(**self**)), previousHop = RREQ.sender **in**
    UpdateRoutingTable(**self**, RREQ)
    MaliciousRouter(**RREQ**, previousHop)
    **dequeue** RREQ **from** requests(**self**)
 }

where the MaliciousRouter submachine is simply:

MaliciousRouter(RREQ, previousHop) ≡
 create_RREP **seq**
 **enqueue** RREP **into** replies(previousHop)



## Malicious ASM – Colluder Program

**if** ¬isEmpty(replies(**self**)) **then** {
  **let** RREP = top(replies(self)) **in**
   **if** RREP.init ≠ **self then** {
    **choose** entry ∈ routingTable(**self**) **with** entry.dest = RREP.init
    **let** previousHop := entry.nextHop **seq**
     **enqueue** RREP **into** replies(previousHop)
    **dequeue** RREP **from** replies(**self**)
   }
 }



## Correctness (1/2)

- *The honest hosts intercept any single blackhole attack*
  - Let $n_0, n_1, \ldots, n_{k-1}, n_k, b$ be the route from the initiator to the blackhole
  - We prove that any fRREP is discarded by $n_k$, i.e. fRREP is not enqueued to $n_{k-1}$
  - The only rule allowing $n_k$ to enqueue fRREP to $n_{k-1}$ is guarded by a condition that verifies the trustworthiness of the route (red rule in Verify)



## Correctness (2/2)

- *The honest hosts intercept any cooperative blackhole attack*
  - Let's consider the worst case: $n_0, c_1, c_2, \ldots, c_k, b$
  - We prove that if fRREP is enqueued to $n_0$ the communication does not start
  - In fact the communication starts (blue rule in Initiator) only after $n_0$ has verified the trustworthiness of the route
  - If at least one honest node is between $n_0$ and b is a special case of interception of single blackhole

# Contribution

- From the application domain viewpoint:
  - Proposal of BN-AODV
  - Thanks to ASMs, the ability of the protocol to intercept all attacks is proved
- From the ASM viewpoint:
  - Application to a complex, real, up-to-date case study



# Future work

- Investigation about greyhole
- Simulations for mitigating
  - the draconian approach of BN-AODV
  - the high overhead
- Implementation in ASMETA